Large Pilot Scale Testing of Linde/BASF Post-Combustion CO_2 Capture Technology at the Abbott Coal-Fired Power Plant

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ABSTRACT

The work summarized in this report is the first step towards a project that will re-train and create jobs for personnel in the coal industry and continue regional economic development to benefit regions impacted by previous downturns. The larger project is aimed at capturing ~300 tons/day (272 metric tonnes/day) CO_2 at a 90% capture rate from existing coal- fired boilers at the Abbott Power Plant on the campus of University of Illinois (UI). It will employ the Linde-BASF novel amine-based advanced CO_2 capture technology, which has already shown the potential to be cost-effective, energy efficient and compact at the 0.5-1.5 MWe pilot scales. The overall objective of the project is to design and install a scaled-up system of nominal 15 MWe size, integrate it with the Abbott Power Plant flue gas, steam and other utility systems, and demonstrate the viability of continuous operation under realistic conditions with high efficiency and capacity. The project will also begin to build a workforce that understands how to operate and maintain the capture plants by including students from regional community colleges and universities in the operation and evaluation of the capture system. This project will also lay the groundwork for follow-on projects that pilot utilization of the captured CO_2 from coal-fired power plants. The net impact will be to demonstrate a replicable means to (1) use a standardized procedure to evaluate power plants for their ability to be retrofitted with a pilot capture unit; (2) design and construct reliable capture systems based on the Linde-BASF technology; (3) operate and maintain these systems; (4) implement training programs with local community colleges and universities to establish a workforce to operate and maintain the systems; and (5) prepare to evaluate at the large pilot scale level various methods to utilize the resulting captured CO_2. Towards the larger project goal, the UI-led team, together with Linde, has completed a preliminary design for the carbon capture pilot plant with basic engineering and cost estimates, established permitting needs, identified approaches to address Environmental, Health, and Safety concerns related to pilot plant installation and operation, developed approaches for long-term use of the captured carbon, and established strategies for workforce development and job creation that will re-train coal operators to operate carbon capture plants. This report describes Phase I accomplishments and demonstrates that the project team is well-prepared for full implementation of Phase 2, to design, build, and operate the carbon capture pilot plant.

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EXECUTIVE SUMMARY

A. Overview of the Technology

Post-combustion CO_2 capture (PCC) technology offers flexibility to treat the flue gas from both existing and new coal-fired power plants and can be applied to treat all or a portion of the flue gas. Among the options for post-combustion CO_2 capture from large coal-fired power plants, solvent-based technologies represent the leading pathway as they have been successfully applied in large scale in other applications such as natural gas processing. However, there are a number of challenges in the use of traditionally available solvent-based technologies, including the need for implementation at very large scale, significant parasitic energy losses, and solvent stability/degradation issues.

Linde and BASF have worked together to develop a post-combustion capture technology incorporating BASF's novel amine-based process along with Linde's process and engineering innovations. This technology offers significant benefits compared to other solvent-based processes as it aims to reduce the regeneration energy requirements using novel solvents that are stable under the coal-fired power plant feed gas conditions. Additionally, Linde has evaluated a number of options and identified engineering solutions for capital cost reduction in large solvent-based post-combustion capture plants.

Table 1. Composition of captured product CO_2 stream

	CO_2 vol.% dry	O_2 * ppmv dry	O_2 # ppmv dry	SO_2 ppmv dry	NO_x ppmv dry	THC ppmv dry	H_2O ¥ vol.% dry
Test 1, PM-1	100	n/a	26.7	0	n/a	0.9	5.36
Test 2, PM-2	100	n/a	31.3	0	n/a	0.8	4.81
Test 3, PM-3	100	n/a	25.2	0	n/a	0.5	3.75
Test 4, SO3 -1	100	n/a	38.0	n/a	n/a	n/a	4.70
Test 5, SO3 -2	100	n/a	38.4	n/a	n/a	n/a	4.99
Test 6, SO3 -2	100	n/a	50.4	n/a	n/a	n/a	5.05
Test 7, NH3 -1	100	30.4	15.0	n/a	n/a	n/a	2.96
Test 8, NH3 -2	100	29.6	15.0	n/a	n/a	n/a	2.98
Test 9, NH3 -3	100	28.7	15.0	n/a	n/a	n/a	2.99
Test 10, ALDH-1	100	22.4	15.0	n/a	n/a	n/a	3.03
Test 11, ALDH-2	100	21.0	14.9	n/a	n/a	n/a	3.08
Test 12, ALDH-3	100	20.3	15.1	n/a	n/a	n/a	3.11

* Average Data Collected with CB&I Trace Oxygen Analyzer
\# Average Data Collected with Linde Trace Oxygen Analyzer
¥ Based on Linde Pressure Reading and Assuming Saturated Product CO_2
n/a = not measured during test

Pilot-scale demonstration of the technology at a 1-1.5 MWe scale has been completed in Wilsonville, AL at the National Carbon Capture Center (NCCC) under the project supported by DOE (project award DE-FE0007453). The pilot plant testing demonstrated all of the performance targets including CO_2 capture rate exceeding 90%, CO_2 purity exceeding 99.9 mol% (dry) – see Table 1, regeneration steam consumption energy as low as 2.7 GJ/tonne CO_2, and regenerator operating pressure up to 3.4 bar absolute. The emission control feature incorporated in BASF's patented dry bed configuration was validated during the long-duration testing. Testing has also confirmed the validation of several unique equipment features incorporated in the pilot plant including high-capacity structured packing, gravity-driven absorber inter-stage cooler, blower positioned downstream of absorber, and the unique reboiler configuration which minimizes solvent inventory and promotes fast response to load changes.

B. Goals and Objectives of the Project

The proposed Phase 2 project is aimed at capturing ~300 TPD (272 metric tonne/day) CO_2 at 90% capture rate from existing coal- fired boilers at the Abbott Power Plant on the campus of University of Illinois (UI) using the Linde-BASF novel amine-based advanced CO_2 capture technology. The overall objective of this project is to design and install a scaled-up system of nominal 15 MWe size that not only meets the minimal requirements of the FOA, but also demonstrates a 10x scale-up in plant size while reducing the risks of project costs overruns. The post-combustion capture (PCC) plant will be integrated with the Abbott Power Plant flue gas, steam and other utility systems, and demonstrate the viability of continuous operation under realistic conditions with high efficiency and capacity. This will be accomplished by conducting parametric testing and then long-term testing to demonstrate that the system can achieve target performance resulting in an economically viable incremental cost of electricity (COE) and CO_2 capture cost at the large commercial scale. The project goal will be accomplished in two phases.

The Phase 1 objectives towards meeting the overall goal have been met and included:

- Defining the project in detail,
- Formulating a project management plan,
- Developing a preliminary plant design to enable cost estimates within ± 20%, and
- Obtaining a host site agreement and other financial commitments to prepare a detailed Phase 2 application

The Phase 1 effort has identified technology gaps and defined risks and mitigation strategies for these risks. A preliminary design, along with concurrent basic engineering and cost estimates, was developed. The preliminary Environmental Health and Safety (EH&S) study determined an air, construction, and water permit strategy. The design of the capture system accommodates the standard operation of the host site – an important factor that will be demanded by power plants that would consider deploying capture systems.

The project team has developed approaches for the long-term utilization of the captured carbon. It is envisioned that the facility will serve as a test bed in the future for a variety of pilot scale utilization technologies. This approach fits well into the US DOE goals and Linde-BASF's overall post-combustion capture technology plan to test the economical validity of the complete carbon capture, utilization and sequestration (CCUS) chain and achieve commercial application by 2025.

The project team has also developed strategies for workforce development and job creation that will specifically aid the coal industry. Program outlines have developed to re-train coal operators so that they can become capture plant operators and train undergraduates from regional universities. This feature enables the training of a future workforce that can design and operate these capture facilities and will provide assistance to workers in the coal industry.

Cooperative Agreement DE-FE0026588 for this project was established on October 1, 2015. This is the final report that summarizes results from the Phase 1 project. The project had three no-cost time extensions granted by DOE to all Phase 1 participants, with the third no-cost extension to end May 31, 2017.

C. Tasks and Milestones Summary

ALL MILESTONES WERE ACHIEVED ON TIME AND ON BUDGET FOR PHASE 1. These results are summarized in Table 2.

Table 2. Project Milestones and Status

Budget Period	Task / Subtask	Milestone Description	Planned Completion	Actual Completion	Verification Method	Status / Comments
1	1	Updated Project Management Plan	10/1/2015	10/1/2015	Project Management Plan File	Completed
1	1	Kick-off Meeting	12/30/2015	12/10/2015	Presentation File	Completed
1	2	TEA completed	3/31/2016	3/31/2016	Presentation File	Completed
1	3	EH&S Study Completed	3/31/2016	3/31/2016	Presentation File	Completed
1	5	Phase I Topical Report Completed	3/31/2016	3/31/2016	Presentation File	Completed
1	1	Host Site Agreement Completed	6/30/2016	6/25/2016	Signed Agreement	Completed

D. Accomplishments by Task

Task 1.0 Project Management Plan

Goals and Objectives:

These activities included monitoring and controlling the project scope, cost, schedule, and risk, and submission and approval of required National Environmental Policy Act (NEPA) documentation. This task included all work elements required to maintain and revise the Project Management Plan, and to manage and report on activities in accordance with the plan.

Summary of Activities:

A Project Management Plan was developed per NETL guidelines and reviewed by NETL. The plan was in place by October 1, 2015. A project kick-off meeting was held at NETL's Pittsburgh, PA facility on December 10, 2015. In order to facilitate the collection and analysis of relevant information, small teams were designated to focus on each of the tasks. A website was also established for secure data sharing amongst the team. Project management meetings were held to coordinate activities surrounding the development of the Phase 2 proposal.

Stakeholder engagement was also pursued as part of the Phase 1 of this project in preparation for Phase 2. Part of this activity included building relationships and outlining activities for Phase 2 that would result in workforce development, training, and professional development. Illinois Eastern Community College (IECC) was selected as a partner for training capture plant operators. IECC currently has programs to prepare personnel for employment in the coal industry. This program provides a means to re-train and create new jobs to overcome unemployment in the coal industry.

We have also developed an alliance with the Association of Illinois Electric Cooperatives (AIEC) and other regional utilities to enable and facilitate the evaluation of capture technology by other end users. Part of the outreach plan is to establish a means to train other plants in a process to evaluate, plan, and implement the retrofit of their facilities with capture technologies.

Task 2.0 – Technology Engineering Design and Economic Analysis

Goals and Objectives:

This report focused on the cost and performance evaluation of a nominal 550 MWe supercritical pulverized coal (PC) utilizing Illinois No. 6 coal as fuel and incorporating the Linde-BASF carbon capture technology in terms of its efficiency, COE, and cost of CO_2 captured. As prescribed by the requirements of the FOA, the analysis followed the approach outlined in the DOE NETL Cost and Performance Baseline for Fossil Energy Plants [Ref. 1] for reference case 12.

Experimental Methods:

The techno-economic evaluation was completed for two versions of the Linde-BASF technology: 1) a previously presented (for a subcritical PC plant) Linde-BASF PCC plant incorporating BASF's OASE® blue aqueous amine-based solvent (LB1) [Ref. 2] and 2) a new Linde-BASF PCC plant incorporating the same BASF OASE® blue solvent that features an advanced stripper inter-stage heater design (SIH) to optimize heat recovery in the PCC process. Table 3 presents a limited degree of details for the BASF OASE® blue solvents used in the current small pilots and targeted to be used for the proposed large pilot project since the characteristics for PCC application constitute commercial trade secrets and are therefore not publishable

Table 3. Updated State-Point Data Table for BASF OASE(R) blue solvent

	Parameter	PCC Pilot at NCCC (1-1.5 Mwe) (Measured)	Future PCC plants (Projected)	Explanation for projected value for future PCC Plants
Table Solvent Properties	Molecular weight (g/mol)	proprietary	proprietary	Same solvent; properties provide excellent performance. Solvent property ranges shown reflect varying concentrations of the solvent amine content.
	Boiling point (°C)	proprietary	proprietary	
	Freezing point (°C)	-5 to 25	-5 to 25	
	Vapor pressure at 40°C (hPa)	proprietary	proprietary	
	Concentration (kg amine/kg solution)	proprietary	proprietary	
	Specific gravity (15°C/15°C)	1.0 – 1.2	1.0 – 1.2	
	Heat capacity at STP (kJ/(kg*K))	2.7 – 4.1	2.7 - 4.1	
	Viscosity at STP (cP)	1.5 – 7.0	1.5 – 7.0	
	Surface tension at STP (dyn/cm)	30 – 50	30 – 50	
Operating Conditions	Absorption pressure (bara)	1.0	0.9 - 1.1	Pressure range is optimal for absorption and available from power plant; maintained with blower.
	Absorption temperature (°C)	30 - 70	30 - 60	Temperature range is optimal for absorption and achieved with DCC
	Absorption equilibrium CO_2 loading (mol CO_2/mol amine)	proprietary	proprietary	Current absorption equilibrium CO_2 loading provides optimal performance.
	Heat of absorption (kJ/mol CO_2)	proprietary	proprietary	proprietary
	Desorption pressure (bara)	1.6 to 3.4	1.6 to 3.5	Higher desorption pressure reduces downstream compression capital and operating costs; there is an upper pressure limit due to high temperature limitation.
	Heat of desorption (kJ/mol CO_2)	proprietary	proprietary	proprietary
	Steam temperature (°C)	130-175	130-175	This is based on both the temperature of the steam supplied by the power plant and optimal process steam temperatures determined from models and simulations.
	Desorption equilibrium CO_2 loading (mol/mol)	proprietary	proprietary	Current desorption equilibrium CO_2 loading provides optimal performance.

The process simulation and modeling for the report were performed using Aspen Plus V8.8. BASF's proprietary thermodynamic and process simulation models were utilized for the detailed modeling, analysis, and optimization of the amine-based PCC plant options. The simulations developed and resulting cost estimates were first validated by reproducing the results of DOE/NETL Case 12 representing a power plant with post-combustion capture incorporating a monoethanolamine (MEA) solvent. The key process performance indicators were then used to determine the incremental capital charges for the power plant with Linde-BASF capture technology by utilizing estimated scaling parameters. The capital cost estimate for the Linde-BASF PCC technology however was based on in-house proprietary costing tools and experience from recent proposals and studies. A previously developed Linde thermodynamic model for solid fuels, consistent with a previously Linde-configured Unisim computational platform, was used in this study to reproduce thermodynamic and physical properties of Illinois No. 6 bituminous coal consistent with the parameters in DOE/NETL Case 12 Reference [Ref. 1]. Within Aspen Plus V8.8, the STEAMNBS and Peng-Robinson property packages were utilized for calculations involving the power plant steam cycle and CO_2 compression, respectively.

Site characteristics, raw water usage, and environmental targets are identical to those detailed in section 2 of the DOE/NETL Case 12 reference [Ref. 1].

The methodology for calculating the cost of electricity over a period of 20 years used in this study is, again, identical as in the DOE/NETL Case 12 reference for 2011 [Ref. 1 and Ref. 3], where COE is used instead of LCOE for cost performance assessment purposes:

The economic assumptions used to derive the above values are summarized in Exhibit 2-14 and Exhibit 2-15 of the DOE/NETL Case 12 reference [Ref. 1].

Results and Discussion:

The results of the techno-economic assessment compared two specific options utilizing the BASF OASE® blue solvent technology (LB1 and SIH) as compared to the DOE/NETL Case 12 reference and are summarized in Table 4.

Table 4. Process Performance and Cost Summary for DOE/NETL Cases Compared to Linde-BASF Technologies

Parameter	NETL Case 11	NETL Case 12	Linde Case LB1	Linde Case SIH
Scenario	No Capture	CO_2 Capture with MEA	CO_2 Capture with OASE® blue	CO_2 Capture with OASE® blue and SIH
Net power output (MWe)	550	550	550	550
Gross power output (MWe)	580.3	662.8	638.9	637.6
Coal flow rate (tonne/hr)	186	257	236	232
Net HHV plant efficiency (%)	39.3%	28.4%	30.9%	31.4%
Total overnight cost ($2011)	1,348	2,415	1,994	1,959
Cost of captured CO_2 with TS&M ($/MT)	N/A	67	52	50
Cost of captured CO_2 without TS&M ($/MT)	N/A	57	42	40
COE (mills/kWh) with TS&M cost included	81.0	147.3	128.5	126.5

Overall, Linde-BASF technologies improve net power plant efficiency and lower capital costs (Figure 1). The net efficiency of the integrated 550 MWe supercritical PC power plant with CO_2 capture is increased from 28.4% with the DOE/NETL Case 12 reference to 30.9% with the Linde-BASF PCC plant previously presented utilizing the BASF OASE® blue solvent [Ref. 2], and is further increased to 31.4% using Linde-BASF PCC plant with BASF OASE® blue solvent and an advanced stripper inter-stage heater configuration (SIH) (Figure 1a).

The Linde-BASF PCC plant incorporating the BASF OASE® blue solvent also results in significantly lower overall capital costs (Figure 1b-c), thereby reducing the COE and cost of CO_2 captured (including \$10/MT CO_2 Transportation, Storage and Monitoring (TS&M) costs) from \$147.25/MWh and \$66.49/MT CO_2, respectively, for the reference DOE/NETL Case 12 plant, to \$128.46/MWh and \$51.81/MT CO_2 for process case LB1, respectively, and \$126.49/MWh and \$50.48/MT CO_2 for process case SIH, respectively. In addition, improved heat recovery through utilization of the advanced flash stripper configuration (AFSC) further reduces PC plant coal consumption and consequently leads to the highest net plant HHV efficiency of 31.7%. With this innovative Linde-BASF PCC process configuration improvement, the COE and cost of CO_2 captured (including \$10/MT CO_2 TS&M costs) can be further reduced to \$125.54/MWh and \$49.94/MT CO_2 for LB1-AFSC.

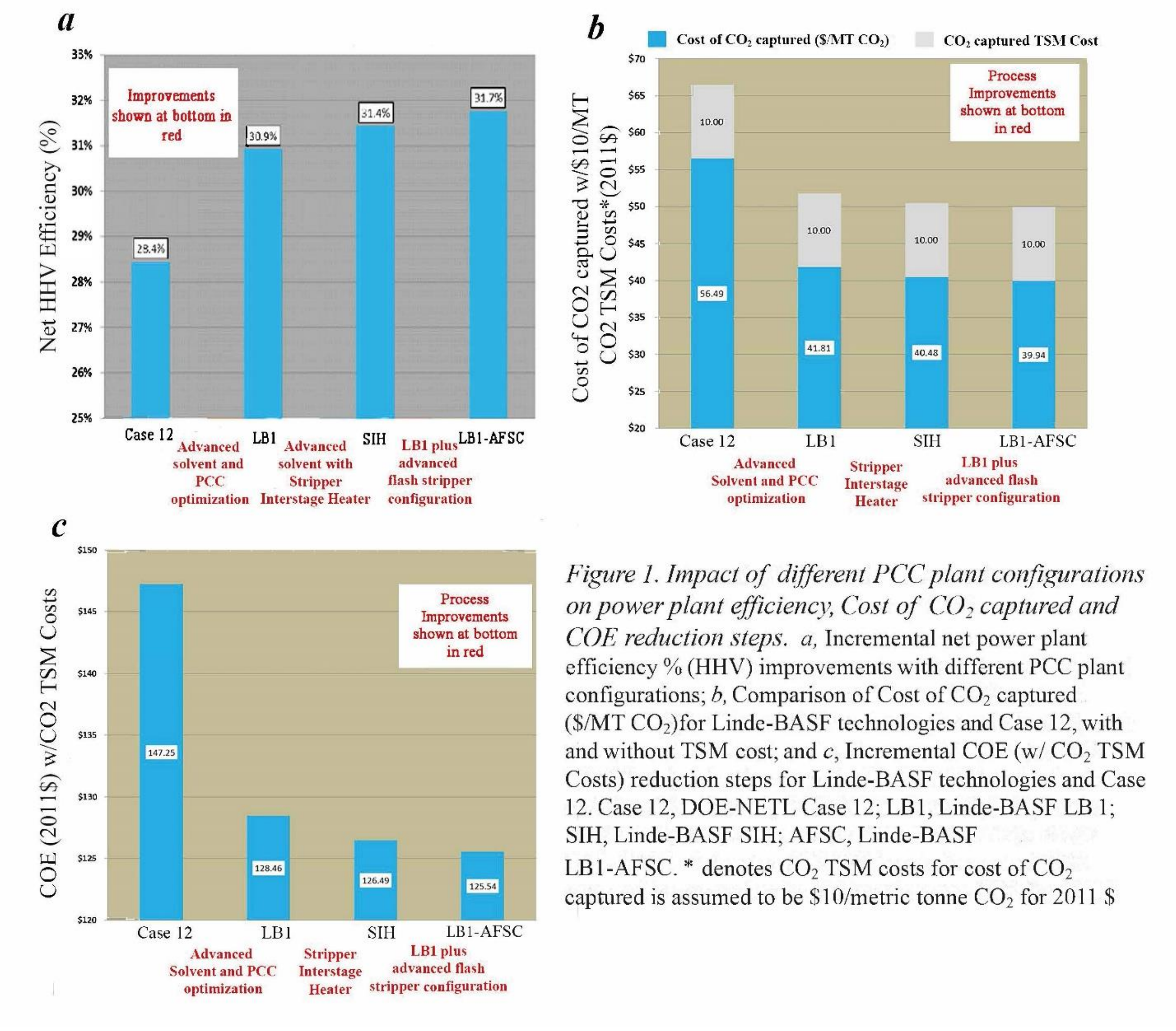

Figure 1. Impact of different PCC plant configurations on power plant efficiency, Cost of CO_2 captured and COE reduction steps. *a,* Incremental net power plant efficiency % (HHV) improvements with different PCC plant configurations; *b,* Comparison of Cost of CO_2 captured (\$/MT CO_2)for Linde-BASF technologies and Case 12, with and without TSM cost; and *c*, Incremental COE (w/ CO_2 TSM Costs) reduction steps for Linde-BASF technologies and Case 12. Case 12, DOE-NETL Case 12; LB1, Linde-BASF LB 1; SIH, Linde-BASF SIH; AFSC, Linde-BASF LB1-AFSC. * denotes CO_2 TSM costs for cost of CO_2 captured is assumed to be \$10/metric tonne CO_2 for 2011 \$

Summary and Conclusions:

With an increasing number of implementations of PCC technology in power plants at very large scale, the learning curve benefits will drive the COE lower, towards the DOE/NETL goal for the cost of captured CO_2 at or below of \$40/tonne by 2030. The development proposed here is the next step along the pathway toward achieving significant reductions in COE of large scale power plants incorporating post-combustion

CO_2 capture in the immediate future. Notably, the Linde-BASF process options presented here have already the potential to lower the cost of CO_2 captured to meet the DOE target of $40/MT CO_2 without CO_2 TS&M costs included at the 550 MWe scale.

Task 3.0 Environmental, Health, and Safety (EH&S) Risk Assessment

Goals and Objectives:

The purpose of the EH&S task was to assess the environmental friendliness and safety of the Linde/BASF PCC technology based on the materials and process being proposed and determine if there are any roadblocks to commercialization. In order to achieve this goal, a preliminary EH&S risk assessment was performed to identify potentially hazardous substances in the pilot exhaust gas and wastewater, as well as process safety risks for the large pilot. The identified risks were then used to complete the NEPA environmental questionnaire as part of Task 1. In addition, the permitting requirements for the large pilot had to be determined and their impacts on the existing Continuous Emissions Monitoring System (CEMS) in conjunction with the CO_2 capture evaluated.

Experimental Methods:

The EH&S assessment is an important investigation to prevent any impediments to the development and commercialization of the Linde/BASF PCC technologies. The risk assessment was performed by engineers in Research and Design (R&D) Group with support from process and development engineers at Linde's Dresden, Germany and the chemical specialists at BASF.

The potential human health and toxicological effects of the solvent were reviewed and guidelines for proper handling, storage and use were outlined in the report. The family of BASF OASE® solvents is protected intellectual property and the product solvent composition has not been tested for its potential health effects. However, BASF used its extensive library of chemical information to derive the properties of the OASE® blue solvent based on the properties of its individual components, which have been tested for effects on human health.

All potential ancillary or incidental air and water emissions, and solid wastes produced from the Linde-BASF technology were identified based on results available from the previous solvent testing and bench or pilot CO_2 capture demonstration projects by Linde and BASF. The project team then estimated the magnitude of the emissions or effluents expected in the large pilot based on the process simulation completed in Unisim.

Additionally, an engineering analysis was conducted to assess the risks associated with potentially hazardous materials arising from the operation of the Linde-BASF large pilot plant. The scope of this risk assessment included not only the solvent, but also other chemicals used in the process, possible by-products that might occur in the system, accumulated waste products, and known effluents and emissions that are anticipated from reactions within the PCC plant. Engineering controls and/or other mitigation strategies were explored and are discussed in detail in the report.

A literature review of Linde's standard procedures for the inherent safe design of all engineering and construction projects was conducted and the results were described in the report. A detailed plan was also developed to address any issues identified during the design and engineering phases through process safety and a hazard and operability study (HazOp).

Finally, activities were conducted to identify all permits, permitting authorities, and other key factors that could significantly affect the implementation of the project. The project team held meetings with multiple regulatory, utility, industry, and compliance stakeholders in order to gain a comprehensive understanding of the permitting and notification pathways necessary for successful implementation of the project. During this process, key issues were considered including information about air, land, water, waste and storm water management, local noise thresholds, stakeholder engagement/hearings, fire service, sanitary sewer connection, and right-of-way setbacks for the adjacent railway and utilities. This information was used to prepare the Phase 2 NEPA Environmental Questionnaires for the project

Results and Discussion:

Pilot testing of the Linde-BASF PCC technology at NCCC in Wilsonville, AL revealed that little to no added emissions of HAPs metals, NOx, SO_2, or SO_3 are produced from the process, and that no significant concentration of the OASE® blue solvent could be found in the air surrounding the plant. The key EH&S risks that were identified, as well as mitigating factors for management of the risks are summarized in Table 5. All possible risk mitigation factors will be applied to ensure the successful build and operation of the pilot and safe implementation of the project. An Environmental Questionnaire for the Phase 2 project was prepared based on the results from the Phase 1 EH&S assessment and the environmental impact information specific to the large pilot project and test site. The project team worked closely with the UI Facility & Services' Compliance Office to provide NEPA information, as well as to determine permitting requirements using the information regarding hazardous and toxic emissions or effluents (wastewater, gas, and solid wastes, etc.) and their impacts on the existing Continuous Emissions Monitoring System (CEMS), in conjunction with the CO_2 capture. Specific to this large pilot project, air, water, and construction permits are expected. During Phase 1 meetings were held with the Illinois Environmental Protection Agency and the Urbana-Champaign Water District to determine timelines and costs for these permits.

Table 5. Environmental, Health, and Safety Issues

Safety and Health Risk	Mitigation Approach
Plant operations safety	•Applied Linde's comprehensive "Safety by Design" guidelines •Safety and operator training
Safety issues arising from improper design and operations/maintenance requirements not identified at design	•Implementation of Linde Gas Standard Requirements •Comprehensive Hazard and Operability study (HAZOP) •Comprehensive Process Safety Reviews (PSR)
Process operations safety	•Safety instrumented systems •Flow restriction and safety interlocks •Automatic safe shutdown capability incorporated in the large pilot plant design •Emergency power supply
Chemical exposure	•Multiple eye wash and emergency showers •Safe locations of vents and blow down •Proper sizing of relief valve and similar devices •Catch pots for capturing any leaks during maintenance
Solvent handling	•Rigorous operating procedures including mandatory usage of Personal Protection Equipment (PPE)
Solvent storage (regulatory requirements)	•OSHA and EPA regulated chemicals with threshold storage volume for process safety management checked. Confirmed solvent is not part of the classified chemicals list with threshold volume.

Summary and Conclusions:

A preliminary but comprehensive EH&S (environmental, health and safety) risk assessment was completed for this project incorporating the Linde-BASF OASE® blue CO_2 capture technology at the Abbott coal-fired power plant on the campus of the University of Illinois. During Phase 2, the design, engineering, construction, operations and testing will take into account the risks and mitigating factors identified in this document in order to safely implement the project. At the end of the operations phase, an updated EH&S report will be prepared highlighting the implementation of the EH&S factors in the project as well as any additional lessons learnt during the implementation. The EH&S report developed for this project is expected to provide a strong basis for EH&S risk handling in further scale-up and commercialization of post-combustion capture technology.

Task 4.0 Technology Gap Analysis and Risk Management

Goals and Objectives

The goals of this task were to identify technology gaps and options to address them both in the implementation of the large pilot in Phase 2 and in future commercialization. Since Linde and BASF have successfully performed bench scale and small pilot scale testing, with the most recent being on a 1.5 MWe pilot plant scale, the main focus of technology gaps was on the scale-up aspects that impact performance, reliability, long term stability of the large pilot and commercial installations.

Experimental Methods:

The technology gap analysis followed a systematic approach to outline both the current state of development of all critical process components and identify the research needs required to develop these components to commercialization. Toward this goal, a brief review of the Linde-BASF PCC technology was described and a process flow diagram was developed to show its integration with a coal-fired power plant. The project team also outlined the potential advantages of the process in terms of efficiency, emissions and cost. Finally, an assessment of each of the major components of the system was performed by assigning them with a current Technology Readiness Level (TRL) and an expected TRL by the time learnings and results of the current large scale pilot testing period have been evaluated and effectively integrated into the process technology.

Subsequently, a summary of the current level of research was outlined, including 1) a description of the learnings gained from past Linde-BASF PCC pilot plant experiences as they apply to critical PCC technology elements, and 2) details of the current level of research on several key components of the PCC process as well as the information and testing needed before process scale up (gaps). Those R&D gaps that will be the focus for Phase 2 efforts were assessed and those R&D gaps that would be investigated through other R&D programs were also identified. The large pilot design R&D gaps (including technology gaps related to the absorber column, stripper column, and heat exchangers) were also rigorously modeled via Linde design and engineering efforts, taking into account the modeling tools developed from experimental bench-scale data provided by BASF using the OASE® blue solvent.

Results and Discussion:

During Phase 1, the project team completed a Technology Gap Analysis report that identifies seven primary technology areas where further development is needed to achieve rapid commercialization. The report uses extensive historic data to show the current TRL status of the technology components and provides recommendations for closing these gaps. The primary gaps studied are shown in Table 6 noting the status of each technology gap together with its expected Phase 2 efforts to address these areas as well as a description of the required steps forward to close the identified R&D technology gaps.

The project team has considered a number of innovative approaches for advanced equipment and process design elements and novel solvent performance characteristics to further reduce total PCC plant cost while minimizing the high energy penalty associated with solvent regeneration. The proposed Phase 2 project will address the identified technology gaps and pave the path forward for large scale commercialization of Linde-BASF OASE® blue technology. Below is a list of the technology gaps that the team proposes to address during the project:

- Absorber column scale-up: performance factors and construction strategy for low costs
- Incorporating a CO_2 recycle to address flue gas composition variability

- Developing control and device-appropriate load-following strategy for the capture plant to enable fast response to variations in power plant load
- Managing flue gas impurities (particulates, SO_3, etc.) that create aerosols and contribute to amine carry-over (Emission control)
- Optimizing operation of the stripper to reduce steam utilization and increase energy efficiency of the CO_2 capture process using advanced stripper configurations and stripper inter stage heating
- Assessing solvent recycle options to help manage condensates containing low solvent concentrations
- Evaluating options for water and wastewater management to reduce impact on the environment and O&M costs

Table 6. Status of Technology Gaps and Steps Required to Close Them

Technology Gap	Description/Comments	Path Forward
Absorber column scale-up	• Uniform vapor and liquid distribution in the absorber • Low cost options to maximize modular shop fabrication and minimize field installation.	• Apply Linde commercial experience to check liquid and vapor distributor designs • Assess and implement low cost column construction strategy and apply experience from the large pilot to single column scaling beyond 12m diameter
Flue gas concentration variability	• The pilot plant design must consider variability in flue gas composition (CO_2, O_2, SO_2, etc.) and cover the full range.	• Recycle CO_2 from stripper to flue gas (FG) at the absorber inlet to increase CO_2 conc. and design direct contact cooler to manage higher SO_2 concentration in FG.
Load following strategy and response	• Abbott power plant operates at varying loads based on University of Illinois campus power and heat load requirements.	• Implement device-appropriate load-following strategy for the capture plant to enable fast response that can be employed for commercial designs.
FG impurities leading to solvent losses	• A high concentration of nanoscale particles and SO_3 and H_2SO_4 molecules in the flue gas can result in significant aerosol formation and increased amine carryover.	• Measure and characterize aerosols in Abbott power plant flue gas and make provisions for reducing aerosol particles in the flue gas at the source. Test the effectiveness of an aerosol control module prior to large pilot plant design.
Regeneration energy optimization	• An advanced stripper configuration is needed to enable full heat recovery from the lean solution to minimize regeneration energy	• Reduce reboiler duty by incorporating stripper inter-stage heating and evaluate additional methods to reduce energy consumption using external waste heat and advanced flash stripper configurations while considering any additional capex.
Solvent Management	• Large scale plants require large quantities of solvent, leading to challenges around delivery logistics, storage, solvent degradation and management of spent solvent and condensate laced with solvent.	• Develop solvent delivery and storage options using BASF's experience • Test portable solvent reclaiming system if necessary to minimize spent solvent volume and assess solvent recycle options to help manage condensates with low solvent concentrations.
Water and Wastewater Management	• Large amount of wastewater with trace amounts of contaminants from (a) cooling water makeup, (b) blowdown discharge, and (c) flue gas condensate may incur high permitting costs or reach capacity limits.	• Evaluate options for treatment or reuse of wastewater such as (a) reverse osmosis (b) water softening to remove scale forming salts, (c) reuse as water makeup to the large pilot plant cooling tower or (d) reuse as process water for Abbott's SO_2 scrubber.

Summary and Conclusions:
The Phase 1 Technology Gap Analysis report provides a broad overview of the Linde-BASF PCC technology, its potential advantages in terms of efficiency, emissions and costs, and presents a plan of research needs to bring the proposed improvements to TRL7 or greater by the end of Phase 2. In summary, this serves as a roadmap to achieving the DOE goal of at least 90% CO_2 capture at costs below $40/tonne.

Task 5.0 – Design, Engineering and Costing of the Large Pilot Plant

Goals and Objectives:
The goals of this task were to design and engineer the large pilot plant, and provide an overall cost estimate for the Phase 2 project with ±20% accuracy. The scope included the equipment and modules inside the battery limit (ISBL) of the post-combustion capture

plant and those outside the battery limit (OSBL) intended to provide the flue gas, electricity, steam, cooling water and other utilities from the host site power plant to the CO_2 capture plant.

Experimental Methods:

The team first identified the need for any modifications at the host site to accommodate CO_2 capture with the Linde-BASF system by conducting site visits to examine the plant in more detail. Lengthy discussions were held between the Linde engineers as well as the engineers and operational staff of the Abbott Power Plant to share the relevant information and documents for a successful integration. Flue gas testing was also performed downstream of the CEMS to determine the flue gas specification to be used in the design. The Linde engineers also assessed the location for a potential CO_2 capture site and plant layout.

This information was assessed to define an engineering design basis for the capture system. Based on the flue gas composition and available temperature and pressure of utilities to be used, BASF provided a technology package including basic design for the capture plant. This was then expanded upon by Linde engineers who developed an overall design for the CO_2 capture plant and its requirements for integration with the Abbott Power Plant. The preliminary basic engineering package described the process for carbon capture including flue gas pre-treatment to the offsite facilities necessary to operate the plant. This engineering package formed the basis for costing the system inside the battery limits (ISBL) of the capture plant. Similarly, the Affiliated Engineers, Inc. group (AEI) developed the engineering for components outside the battery limits (OSBL) of the capture system and determined the integration of the flue gas and utilities from the power plant to the CO_2 capture plant on the plot plan. Both the ISBL and OSBL teams prepared preliminary process flow diagrams (PFDs), piping and instrumentation diagrams (P&IDs) and heat and material balances to visualize assumptions and ensure consistent treatment of plant integration. The overall capex of the large pilot was estimated from the separately developed ISBL and OSBL cost estimates and the size and scope of the plant was optimized to reduce the potential for cost overruns.

Results and Discussion

The Abbott Power Plant is a stoker coal-fired boiler with a high excess air flow. As a result, the anticipated flue gas contains a low percentage of CO_2 compared to a conventional pulverized coal-fired power plant as shown in Table 7 below. To accommodate this, the plant was designed to capture approximately 300 TPD (272 metric tonne/day) based on a recovery rate of 90%. While the as-received flue gas will be directly treated in the base scenario, other tests will also be conducted with a recycle stream of the captured CO_2 fed to the absorber inlet to increase the CO_2 concentration of the flue gas influent and mimic the flue gas conditions of a typical conventional PC power plant.

A preliminary basic design package for the pilot plant was produced with the following documents (i) design basis, including feed conditions (i.e., actual flue gas pressure, temperature, flow rate, gas composition and contaminant levels as measured during the flue gas testing; Table 7); (ii) process design,

Table 7. Anticipated Flue Gas Feed for Capture System

Flue Gas Conditions	Exit Stream Values of FGD
Flow Rate	171,009 lb/hr (77,638 kg/hr) (slightly varies with test cases)
Pressure	0.2 psig (1.4 kPa, guage)
Temperature	200° F (93.3° C)
Composition	5.7%mol CO_2, 14.4%mol H_2O, 68.8%mol N_2, 10.30%mol O_2, 0.8%mol Ar, 68 ppmv SO_2 (max 200 ppmv), 211 ppmv NO_x, 4.1 mg/Nm^3 particulate matter

process flow diagram, process descriptions, material balances, utility consumption; emissions and effluents; (iii) equipment list; (iv) process data sheet for all equipment and mechanical datasheets and piping and instrumentation diagrams.

The Abbott Power Plant will provide the major utilities for the carbon capture pilot while the Phase 2 project will manage the discharge of the waste water from the direct contact cooler and blowdown water from the cooling tower of the PCC pilot plant with appropriate environmental permitting. Due to the high demand for cooling water, an auxiliary cooling tower will also need to be built on site to supplement the needs of the capture system. A potential site for the proposed carbon capture pilot was located NW of the power plant in an open lot. The proposed space provides sufficient room for the construction of the capture system and auxiliary cooling tower.

Based on the design and engineering activities, the Phase 2 project is estimated to have a total project value of approximately $76 million. A detailed work plan and schedule for the Phase 2 project was also created to execute the design, engineering construction and operation of the pilot plant over a period of 48 months.

Summary and Conclusions:
The preliminary design and basic engineering was successfully completed for a nominal 15 MWe pilot incorporated with the Linde/BASF carbon capture technology. Upon successful completion of Phase 2, this project is expected to have significant impact on the speed of commercialization of this advanced solvent-based PCC technology, and thereby meet the anticipated need for such plants beyond 2020. This will also provide a clear pathway to commercial viability of captured CO_2 utilization.

Task 6.0 Phase 2 Application Preparation.

The information developed during execution of the previous tasks was used to develop a Phase 2 proposal that was submitted before the March 31, 2016 deadline. Supported by the rest of the project team, UI prepared a Phase 2 proposal compliant with the US DOE-NETL guidelines listed in DE-FOA-0001190 including the information listed in the relevant Attachments.

As a part of this task, the team provided US DOE-NETL with documentation necessary for NEPA compliance. Other activities included planning of detailed plant engineering, costing, and vendor arrangements, construction and commissioning strategies, testing and data analysis, and economic analysis and reporting.

Summary and Conclusions:
Additional documentation for the Phase 2 proposal that was required by June 30, 2016, included the following:

- Executed Financial Agreements due 6/30/2016
- Executed Host Site Agreements due 6/30/2016
- Updated Representations and Certifications due 6/30/2016

All the required documents listed above were supplied before the due date. **Phase 2 of this project is ready for full implementation (i.e. design, build, operate).**

E. Summary, Conclusions, and Issues for Further Study

The Phase 1 effort has demonstrated that implementation of this project is feasible at the Abbott Power Plant and can meet key goals and objectives defined by NETL-DOE. The design and installation of a scaled-up system of nominal 15 MWe size will demonstrate the viability of the Linde/BASF capture technology under realistic conditions with high efficiency and capacity. Strategic alliances with various stakeholder groups have been formed to enable workforce development and education opportunities for students. The workforce development piece is especially targeted at aiding workers from the coal industry by training them to be operators of the capture plants. This project will also lay the ground work for follow on projects that pilot utilization of the captured CO_2 from coal-fired power plants. The next step is the funding and implementation of Phase 2, i.e. design, build, operate. This would result in a facility to enable large scale pilot R&D for CCUS.

I. TECHNICAL REPORT BODY

A. Technology Description

Among the options for post-combustion CO_2 capture from large coal-fired power plants, solvent-based technologies represent the leading pathway as they have been applied in large scale in other applications such as in natural gas processing. However, there are a number of challenges in the use of traditionally available solvent-based technologies, including the need for implementation at very large scale, significant parasitic energy losses, and solvent stability/degradation issues.

Linde and BASF have worked together to develop post-combustion capture technology incorporating BASF's novel amine-based process along with Linde's process and engineering innovations. This technology offers significant benefits compared to other solvent-based processes as it aims to reduce the regeneration energy requirements using novel solvents that are stable under the coal-fired power plant feed gas conditions. Additionally, Linde has evaluated a number of options and identified engineering solutions for capital cost reduction in large solvent-based post-combustion capture plants.

As indicated in Figure 2, the overall PCC process resembles a typical amine-based CO_2 capture process configuration, but also includes patented innovations leading to high efficiency of CO_2 capture.

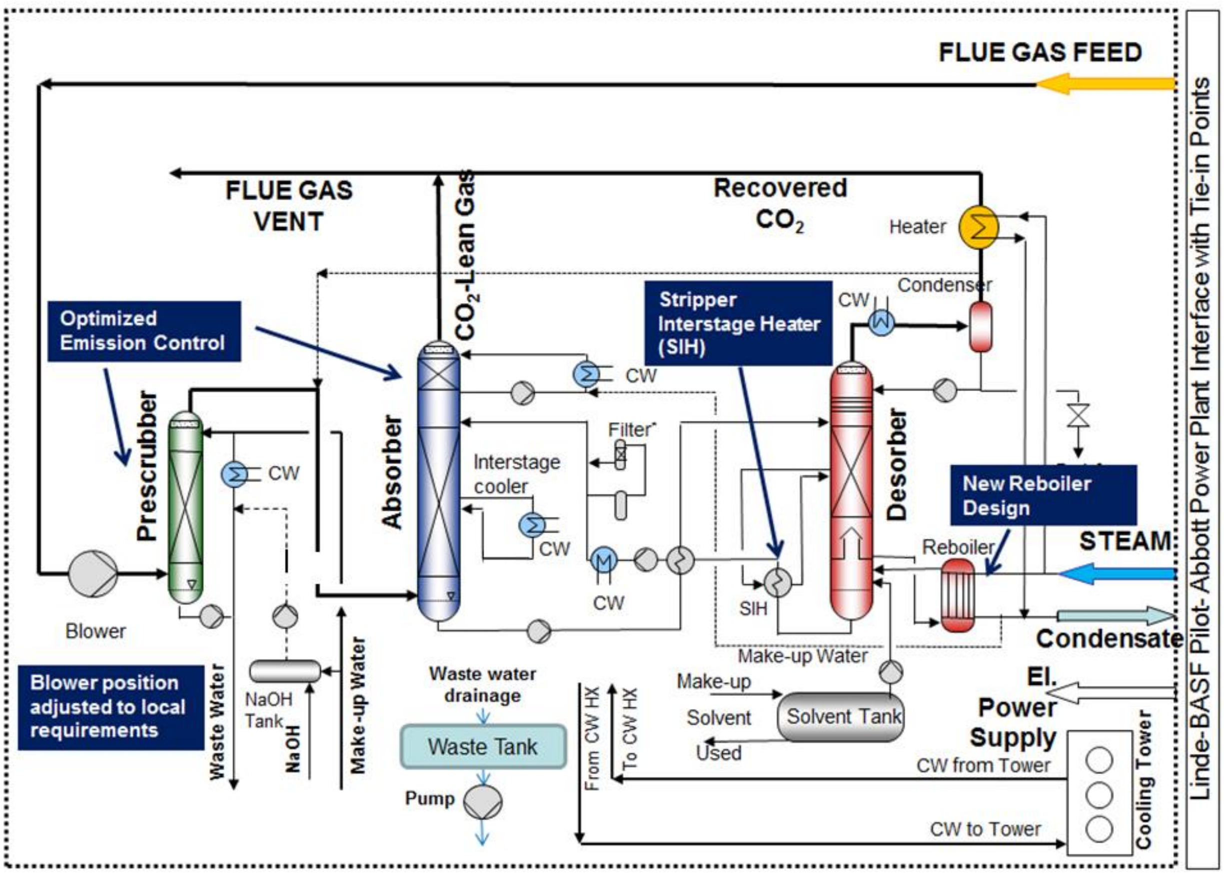

Figure 2. Process Flow Diagram of PCC Plant at Abbott Power Plant

The main process units are listed below. The key benefits of the integrated have been discussed in more detail in a paper presented at the GHGT-9 in 2008, and listed in the Bibliography as a Reference 4.

Flue gas blower that provides sufficient pressure to overcome the pressure drop across the pre-scrubber and absorber. The location of the flue gas blower will be adjusted to suit the Abbott Power Plant site-specific equipment arrangement in the most cost-effective manner.

a) Integrated pre-scrubber and direct contact cooler (DCC), which reduce SOx content below 5 ppm and simultaneously cool down the flue gas stream from ~ 93 °C to ~35-40 °C.

b) Innovative and patented water wash section at the top of the column to reduce amine losses, even in the presence of aerosols,

c) A gravity-driven inter-stage cooler for the absorber that eliminates the pump and the controls,

d) High-capacity structured packing that reduces the diameter of the absorber, thereby enabling a larger single train plant construction,

e) Solvent-solvent heat exchanger designed to operate over a wide range of temperature approaches which provides the opportunity to optimize the performance and capital cost trade-off,

f) Regenerator designed for operation at pressures up to 3.4 bars with the potential to significantly reduce CO_2 compression energy as well as eliminate the bulky first stage of the CO_2 compressor, thereby resulting in capital cost savings,

g) Innovative plate & frame design of the reboiler which minimizes thermal degradation of the solvent and provides for a lower solvent inventory and faster dynamics to respond to load changes,

h) Stripper Inter-stage Heater (SIH) used to enhance energy efficient CO_2 stripping from the solvent by recovering heat from the lean solvent to provide intermediate reboil, thereby reducing energy consumption of solvent regeneration,

i) Variations of the stripper-reboiler flashing configuration, which are being evaluated for an ultimate reduction of solvent regeneration energy.

j) Optional CO_2 recycle stream, provided to evaluate the effect of plant loading and variable CO_2 concentration in the flue gas on overall energy consumption, and to limit the effects of power plant loading on flue gas CO_2 mol% fluctuations.

B. Technology Performance to Date

Linde and BASF have been jointly developing, optimizing, and demonstrating advanced PCC technology since 2007. The major milestones achieved so far include:

- Formulation and successful testing of BASF's advanced, amine-based, OASE® blue solvent for efficient CO_2 capture from low pressure sources, such as CO_2 contained in the flue gas from coal and natural gas based power plants
- Design of an advanced PCC plant targeted to minimize the cost of electricity from power plants with 90% CO_2 capture
- Successful pilot demonstration of proposed PCC technology at 0.5 MWe capacity level in Niederaussem, Germany and 1.5 MWe capacity level at the National Carbon Capture Center (NCCC) in Wilsonville, AL.

Validation of joint Linde-BASF PCC technology started with 0.5 MWe pilot plant tests in Niederaussem in 2010 and continued with parametric testing of a 1.5 MWe pilot plant NCCC in Wilsonville, Alabama in 2015.

Pilot plant at the RWE Power Plant in Niederaussem, Germany

In partnership with BASF, and RWE Power, Linde Engineering designed, manufactured, and installed a small pilot PCC plant integrated with RWE Power's 1,100 MW dry lignite fired power plant in Niederaussem, Germany, capable of recovering ~ 7.2 TPD of CO_2 from ~ 1,500 Nm3/h flue gas slipstream. Comprehensive instrumentation with more than 200 data points and corresponding process control systems enabled reliable and accurate measurements and evaluation of key solvent and process parameters.

The slipstream flue gas from the RWE Power generation plant was cooled down to ~ 40°C by a direct contact cooler unit. A flexible, modular absorber designed by Linde allowed optional by-passing of some

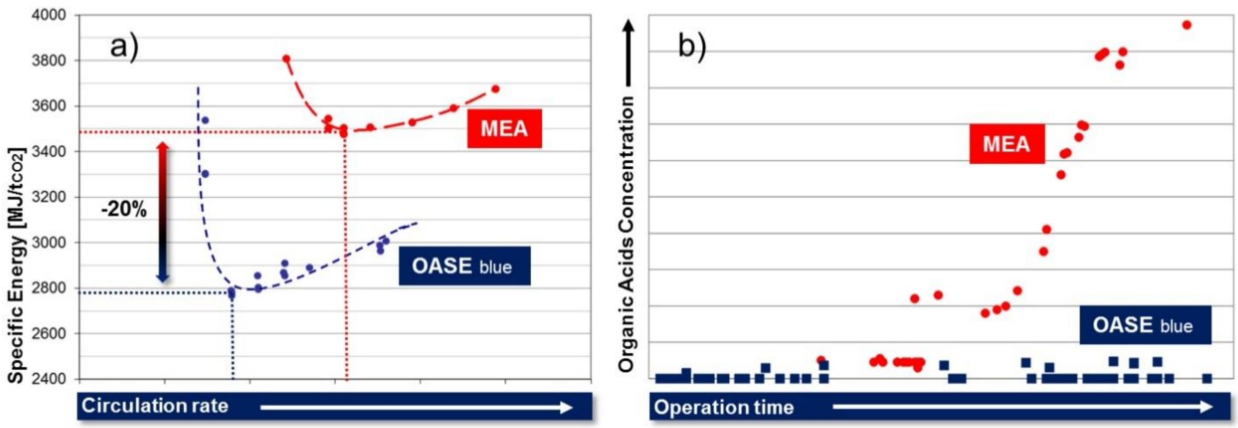

Figure 3.BASF Solvent Circulation Rate and Stability. a) Solvent circulation rate shows a 20% energy reductrion for OASE® blue vs. MEA, b) Solvent stability test shows that OASE® blue is stable over 5,000 hours while MEA is significantly degraded.

portions of the column in order to evaluate the effect of bed packings and corresponding heights. An inter-stage cooler was also connected in a flexible way to allow withdrawal of the solvent from different locations. A water wash section was installed at the top of the absorber in order to determine optimal operating conditions to minimize VOC and solvent emissions along with energy consumption.

During the initial phase of the pilot testing in Niederaussem, both MEA and the new BASF solvent (now identified as OASE® blue) were tested for a 6-month duration to assess both performance and solvent stability. As illustrated in Figure 3, the new BASF solvent enables ~ 20% energy reduction for solvent regeneration, along with significantly lower solvent circulation rate which in turn reduces the power requirement for rich and lean solvent circulations pumps. The lower solvent circulation rate observed with the BASF solvent also leads to reduction of the absorber and stripper column diameters for a given flue gas capacity, and, hence, leads to capital cost reduction.

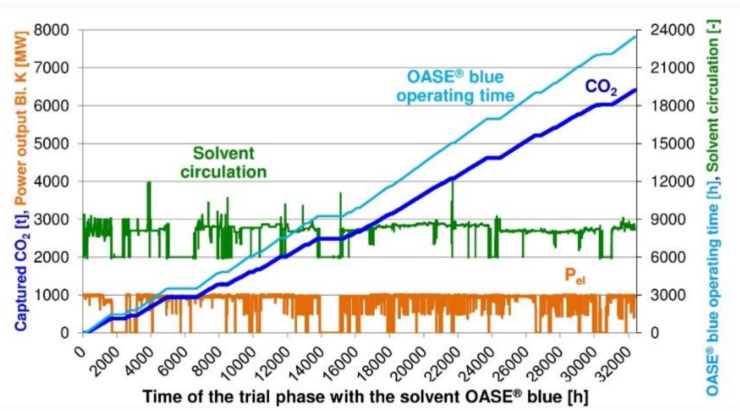

Figure 4. BASF OASE blue performance during long-term testing in the Niederaussem pilot plant

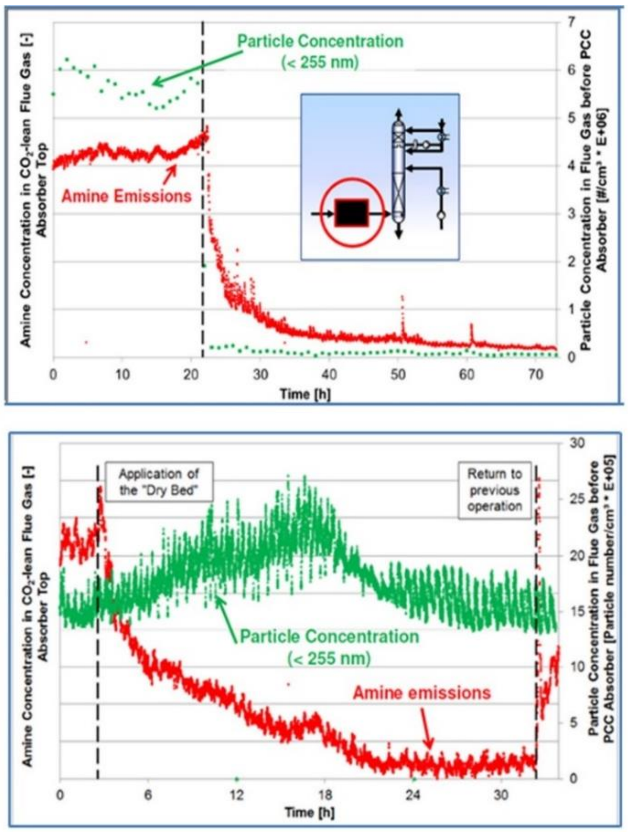

Figure 5. Results of optimized emission reduction systems (pre-treatment and dry bed) tested in the Niederaussem pilot plant show reduced emissions.

Further, reduced column dimensions result in an increase of the single train capacity of the PCC plant that can be built. Figure 3b also shows the measurement of heat stable salts (an indicator of the degradation of the solvent) for both MEA and OASE® blue over test duration of 5000 hours. The test measurements with MEA show that the solvent degradation is rapid after about 2,500 hours whereas the OASE® blue remains stable over the entire duration of measurement. Following the initial testing for solvent selection, long term tests (>26,000 hours) were conducted in the Niederaussem pilot plant to confirm reliability of operation and consistency of performance with the novel solvent as illustrated in Figure 4.

More recent tests focused on optimizing the emission reduction systems, especially amine aerosol emissions caused by dust. Multiple methods were considered, e.g., water wash, acid wash, dry bed, wet electric precipitators (WEP), etc. While WESPs were found to induce aerosol formation, dry bed and flue gas pre-treatment options were found to be effective in significantly reducing emissions (Figure 5). The dry bed configuration, implemented in the 1.5 MWe pilot plant at NCCC, is discussed below.

The pilot plant was also designed to allow testing of various material alternatives, in different places along the PCC pilot plant, as illustrated below in Figure 6. Based on initial tests performed in the small pilot plant in Niederaussem, a number of material alternatives could be employed in order to reduce capital cost of large commercial PCC plants. More information on the results is in Moser et al. [Ref. 5]. This article describes capture process configuration optimization measures and experiments to examine solvent performance during the 18-month pilot plant testing programme at Niederaussem.

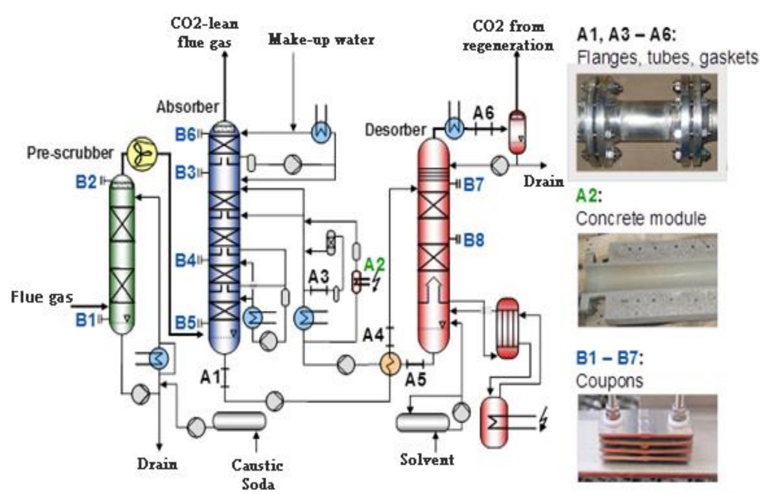

Figure 6. Pilot plant testing of construction materials

Pilot plant at National Carbon Capture Center (NCCC) in Wilsonville, AL

Significantly improved critical properties of the new BASF solvent, combined with advanced designs of the absorber, stripper and corresponding wash units, allow expansion of the operating envelope of the entire carbon capture plant, making it possible to achieve the targeted degree of CO_2 capture with significant energy savings while minimizing the environmental impact by reduced gas emissions, as well as liquid and solid waste disposals. The Linde-BASF team in conjunction with other partners designed, engineered, and built a 1.0-1.5 MWe slipstream pilot plant at the NCCC. This pilot was commissioned during 2014 and started operations and testing in January 2015. Images of the installed plant are shown in Figure 7.

Figure 7. 1.5MWe Pilot Plant at the National Carbon Capture Center (NCCC)

Within a week of startup, steady state operations were achieved and the pilot plant was operated over a range of conditions to validate performance targets. The initial operations and testing phase validated a number of unique design features within the pilot unit. These include (i) high capacity structured packing in the absorber sections, (ii) gravity flow absorber inter-stage cooler, (iii) operation of blower downstream of the absorber, with the absorber operated at slightly below atmospheric pressure, (iv) a unique reboiler design with potential for cost savings at large scale, and (v) operation of the emission control configuration designed in the pilot.

The parametric testing campaign at the National Carbon Capture Center (NCCC) was completed on December 22, 2015 (Table 8). The pilot plant was run continuously subject to the flue gas and steam availability from NCCC. From the start of pilot plant operations through December 22, (i) 5,096 hours of solvent circulation was achieved, (ii) 3,841 hours of steam flow was maintained for either solvent circulation or CO_2 regeneration and (iii) 2,589 hours of operation on the flue gas was achieved. The average CO_2 capture rate during operations, including time taken during ramping the pilot plant and that between tests, was 89%.

Table 8. Summary of Parametric Testing Performed in Wilsonville Pilot Plant

#	Key variable	Status
1	Flue gas flow rate	7,500 to 15,750 lbs/hr
2	Flue gas temperature to absorber	86° F to 104° F
3	Treated gas temperature exit absorber	86° F to 115° F
4	Lean solution temperature to absorber	104° F to 140° F
5	Inter-stage cooler	On (104° F) / Off
6	Regeneration pressure	1.6 to 3.4 bars
7	Solvent circulation rate	Varied from 80 to 120%
8	CO_2 capture rate	• 90% typical • Varied from 85% to >95%

Operations and testing were performed at 3.4 bar regenerator pressure, the highest design pressure for the regenerator at 10,500 lbs/hr flue gas flow rate. Several tests were performed to assess energy optimization. The initial test results indicate that the specific energy consumption in the regenerator at different pressures is similar. The key benefit of the higher regeneration pressure is expected to be a reduction in the energy required for compression of CO_2, thereby decreasing the compressor operating costs. Further, the 3 bar inlet pressure to the CO_2 compressor enables elimination of the first stage which is a high volume flow stage, thereby enabling significant reduction of compressor costs.

Table 9 summarizes key performance targets achieved in PCC pilot plants in Niederaussem (PP1) and in Wilsonville (PP2), while Table 8 provides ranges of process parameters tested at the PCC pilot plant in Wilsonville, AL. Additional discussion on the results from testing of the 1.5 MWe PCC pilot plant at Wilsonville can be found in references 6 and 7.

Table 9. Key Performance Parameters Achieved in Pilot Plant in Niederaussem (PP1) and Pilot Plant in Wilsonville (PP2)

Test/Performance Attribute	PCC Pilot Plant	Key Results	Remarks (Results vs. Targets)
Solvent selection	PP1	Two solvents screened following benchmark testing with MEA. OASE® blue selected	Solvent selected to optimize performance, emissions, and cost
CO_2 capture rate	PP1, PP2	Recovery > 90%	Achieved
CO_2 purity	PP1, PP2	Purity > 99.9% (dry bases)	Achieved
Plant capacity	PP1, PP2	• PP1: 7.2 tonnes/day (0.45 MWe) • PP2: >25 tonnes/day (1.5 MWe)	Achieved
Regenerator steam consumption	PP1, PP2	~ 2.8 GJ/tonne-CO_2 (Intrinsic energy requirement)	Achieved (20% lower than MEA) ~ 2.7 GJ/tonne-CO_2 observed in PP 2
Cyclic capacity	PP1, PP2	>20% compared to MEA	Achieved
Emissions control testing	PP1, PP2	Identified and validated BASF/RWE patented dry bed configuration of water wash unit to reduce emissions. Aerosol control configuration in flue gas stream tested and evaluated	Incorporated in PP2 design. Detailed isokinetic measurements (flue gas & treated gas) performed to confirm effectiveness of emissions control options (such as dry bed configuration) for high aerosol content flue gas, in particular flue gas with a high nanoparticle size particle density.
Regenerator operating pressure	PP2	Pressure up to 3.4 Bara	Achieved & confirmed benefits for compressed CO_2 production
Materials of construction	PP1	Wide range of materials (CS, SS, concrete with PP inliner, FRP, etc) tested in sections and in coupons	Enabled optimized material specifications for PP2 and for commercial cases
Validation of unique process features	PP1, PP2	• High capacity packing in the absorber column • Blower downstream of absorber (PP2) • Unique two-phase flow reboiler design (PP2)	Design improvements for reducing the energy required for solvent regeneration through heat integration were identified. Advanced stripper designs result in <2.5 GJ/tonne CO_2
Long-term testing for solvent stability assessment	PP1, PP2	• PP1: >26,000 hrs (>3 years) of testing • PP2: ~ 1,500 hrs of continuous testing under steady state conditions	• PP1: Achieved • PP2: Long term testing successfully completed from May through July 2016.

C. Design Requirements/Assumptions and TEA

A techno-economic evaluation was performed of the technology following the methods and assumptions outlined in the DOE/NETL Baseline reports for reference case 12. The analysis assumed that the PCC technology was installed in a 550 MWe supercritical pulverized coal (PC) power plant utilizing Illinois No. 6 coal as fuel. Three versions of the Linde-BASF PCC technology were assessed: 1) based on a previously presented (for a subcritical PC plant) Linde-BASF PCC plant incorporating BASF's OASE® blue aqueous amine-based solvent (LB1[1]) [Ref. 2], 2) a new Linde-BASF PCC plant incorporating the same BASF OASE® blue solvent that features an advanced stripper inter-stage heater design (SIH) to optimize heat recovery in the PCC process and 3) an advanced CO_2 rich-CO_2 lean solvent cross exchanger split configuration that improves energy performance but may increase capital costs(LB1-AFSC). As shown in Figure 2, the SIH design will be validated for the Linde-BASF PCC plant as part of the Phase 2 large pilot build, however the AFSC configuration will only be modeled.

Table 10. Supercritical PC Plant Study Configuration Matrix

Steam Cycle, MPa/°C/°C (psig/°F/°F)	24.1/593/593 (3500/1100/1100)
Condenser Pressure, mm Hg (in Hg)	50.8 (2)
Boiler Efficiency, %	88
Cooling water to condenser, °C (°F)	16 (60)
Cooling water from condenser, °C (°F)	27 (80)
Stack temperature, °C (°F)	32 (89)
SO_2 Control	Wet Limestone with Forced Oxidation
FGD Efficiency, %	98
NOx Control	LNB w/OFA and SCR
SCR Efficiency, %	86
Ammonia Slip (end of catalyst life), ppmv	2
Particulate Control	Fabric Filter
Fabric Filter efficiency, %	99.8
Ash distribution, Fly/Bottom	80% / 20%
Mercury Control	Co-benefit Capture
Mercury removal efficiency, %	90
CO_2 Control	BASF OASE® Blue Technology
CO_2 Capture, %	90
CO_2 Sequestration	Off-site Saline Formation

Detailed techno-economic evaluations were accomplished by utilizing Aspen Plus software as a generalized computational platform for rigorous calculations of physical and thermodynamic properties of water, steam, and multi-component mixtures, along with related material and energy balances around each individual unit operation of the integrated power plant with CO_2 capture system. Specifically designed for parametric studies of key PCC process parameters, BASF's proprietary chemical process simulation package has been used for final, accurate predictions of mass and heat transfer rates, as well as for the kinetics of complex chemisorption reactions between CO_2 and solvent components. Resulting performance parameters of the optimized PCC plant have been fully integrated with the Aspen Plus simulation of the PC power plant supercritical steam cycle to produce a complete model of the entire power plant with post-combustion CO_2 capture to investigate the benefits of PCC energy performance improvements on the overall power plant energy performance in addition to capital and operating costs.

The key system assumptions used in the study are identical to those used in the DOE/NETL Case 12 reference and are highlighted in Table 10.

[1] LB1 was analyzed using NETL 2007 report for Cost and Performance Baseline for Fossil Energy Plants DOE/NETL-2007/1281 which used a subcritical PC plant as the reference PCC case and 2007$. This baseline report has since been replaced by DOE/NETL-2010/1397.

Site characteristics, raw water usage, and environmental targets are identical to those detailed in section 2 of the DOE/NETL Case 12 reference [Ref. 3].

The methodology for calculating the cost of electricity over a period of 20 years used in this study is, again, identical as in the DOE/NETL Case 12 reference for 2011 [Ref. 1 and Ref. 3], where COE is used instead of LCOE for cost performance assessment purposes:

$$COE = \{(CCF)*(TOC) + OC_{FIX} + (CF)*(OC_{VAR})]\}/ [(CF)*(aMWh)]$$

In addition, the cost of CO_2 captured, (including \$10/MT CO_2 TS&M costs) was calculated using:

$$\text{Cost of } CO_2 \text{ Captured} = \{COE_{withTS\&M} - COE_{reference}\}\$/MWh \, / \, \{CO_2\ Captured_{withremoval}\}\ tonnes/MWh$$

The following economic parameters were used for COE and cost of CO_2 captured calculations:
DOE/NETL Case 12 reference (2011) Capital Charge Factor (CCF) = 0.1240

The economic assumptions used to derive the above values are summarized in Exhibit 2-14 and Exhibit 2-15 of the DOE/NETL Case 12 reference [Ref. 1]. Consequently, the calculated COE and cost of CO_2 captured values in this study have been expressed in 2011\$ to be able to consistently evaluate the influence of the novel PCC technology on the incremental reduction of COE as compared to the DOE/NETL Case 12 reference (2011\$).

The total plant cost (TPC) for the novel Linde-BASF PCC technology was estimated based on Linde's proprietary methodology of estimating the cost for new, commercial process plants, which included as many actual recent vendor quotes as available based on recent commercial proposals and studies. The accuracy of the final PCC plant cost is estimated to be within +/- 30% in this study. As per DOE/NETL requirements, the resulting TPC also includes 20% process contingency, as well as 4% project contingency.

Table 11 summarizes the major capital costs for the DOE Reference Case 12 and compares this against the three selected Linde-BASF options for PCC.
Additionally, for this study, the total overnight costs (TOC) of the entire PC plant integrated with PCC technology were calculated using the same methodology as in the DOE/NETL Case 12 reference [Ref. 1]:

TOC = TPC + Preproduction Costs (PPC)+ Inventory Capital (IC) + Initial Cost for Catalyst and Chemicals (ICCC)+ Land & Other Owner's Costs (LOOC) + Financing Costs (FC)

where 1) TPC is the total capital cost of the complete PC plant integrated with PCC, 2) PPC are the sum of costs of 6 months labor, 1 month maintenance materials, 1 month non-fuel consumables, 1 month waste disposal, 25% of 1 month's fuel cost, and 2% of TPC, 3) IC are the costs of 60 day supply of fuel and consumables at 100% CF plus 0.5% of TPC in spare parts, 4) ICCC is the cost of 0.193% of TPC, 5) LOOC are the costs of 0.0459% of TPC (Land) plus 15% of TPC for other owner's costs, and 6) FC are the costs equivalent to 2.7% of TPC [Ref. 1]. The first step in validating the modeling approach was to reproduce material streams and related energy balances around the PC boiler as reported in DOE/NETL Case 12 reference [Ref. 1]. As detailed in the previous TEA report for small scale pilot [Ref. 2], it has been previously confirmed by UniSim process simulation that the PCC plant-integrated PC steam cycle with incorporated Illinois No. 6 coal properties and feed rates successfully predicts the flowrates, pressures, and temperatures for high-pressure steam and reheated IP steam based on specified boiler feed water and cold reheat stream flowrates, along with exactly the same composition and temperature of the flue gas, including bottom ash and fly ash content. As done previously in the 2012 TEA report [Ref. 2], the next step was to

Table 11. Itemized Total Plant Capital Cost ($ x 1000, 2011$ price basis)

Item	Case 12	Linde-BASF LB1	Linde-BASF SIH	Linde-BASF LB1-AFSC
Coal and Sorbent Handling	56,286	53,209	52,638	52,273
Coal and Sorbent Prep & Feed	27,055	25,576	25,302	25,126
Feedwater & Miscellaneous BOP Systems	123,565	116,811	115,558	114,755
PC Boiler	437,215	413,317	408,882	406,043
Flue Gas Cleanup	196,119	185,399	183,410	182,136
CO_2 Removal	505,963	257,191	245,120	243,415
CO_2 Compression & Drying	87,534	63,738	60,746	60,324
Heat and Power Integration	0	0	0	0
Combustion Turbine/Accessories	0	0	0	0
HRSG, Ducting & Stack	45,092	42,627	42,170	41,877
Steam Turbine Generator	166,965	157,839	156,145	155,061
Cooling Water System	73,311	69,304	68,560	68,084
Ash/Spent Sorbent Handling System	18,252	17,254	17,069	16,951
Accessory Electric Plant	100,255	94,775	93,758	93,107
Instrumentation & Control	31,053	29,356	29,041	28,839
Improvements to Site	18,332	17,330	17,144	17,025
Buildings & Structures	72,402	68,445	67,710	67,240
TPC without PCC	1,365,902	1,291,242	1,277,387	1,268,517
PCC Cost	593,497	320,928	305,866	303,739
Total Plant Cost (TPC)	1,959,399	1,612,170	1,583,252	1,572,255
Preproduction Costs	60,589	53,162	52,494	52,216
Inventory Capital	43,248	39,899	39,455	39,208
Initial Cost for Catalyst and Chemicals	3,782	3,111	3,056	3,034
Land	899	740	727	722
Other Owner's Costs	293,910	241,826	237,488	235,838
Financing Costs	52,904	43,529	42,748	42,451
Total Overnight Costs (TOC) (2011$)	2,414,731	1,994,436	1,959,218	1,945,725

incorporate the specified performance of the wet Flue Gas Desulphurization (FGD) scrubber in order to accurately predict the flow, pressure, temperature, and composition of the feed stream to the PCC plant.

The most important step in verifying/calibrating the simulation model was to tune the isentropic efficiencies of all steam turbines as well as CO_2 compressors to match the steam turbine power generation and CO_2 compression energy of the DOE/NETL Case 12 reference in order to reproduce the reported pressure, temperature, and flowrate values of all steam and liquid water streams in the steam-water cycle reported in the DOE/NETL Case 12 reference study. This tuning enabled consistent energy performance comparisons

Table 12. Specific Energy Demand for 90% CO_2 Capture and Compression to 2215 psia

Utility	NETL-MEA	Linde-BASF LB1	Linde-BASF SIH
Reboiler Duty, GJ/MT_CO_2)	3.61	2.61	2.30*
Cooling Duty (MS_{th}hr)/(MT_CO_2)	1.64	1.12	0.94
Electrical Power (kW_ehr/MT_CO_2)	119.9	102.95	104.16**

*Effect of stripper inter-stage heater (SIH): semi CO_2 lean solvent is reheated by hot CO_2 lean solvent exiting stripper

**Effect of additional solvent pump for SIH configuration adds 636 kW of electrical power

of the Linde-BASF PCC technologies presented in this study against the DOE/NETL Case 12 reference and each other.

A series of simulations were performed with various operating parameters of the PCC plant incorporating the Linde-BASF technology and with different levels of process integration with the PC power plant. The Linde-BASF PCC plant was designed in all cases to minimize energy requirements for CO_2 recovery and compression. Table 12 summarizes the resulting energy requirement elements for CO_2 capture and compression for the two main Linde-BASF process options described in this study, LB1 and SIH. The results of the techno-economic assessment are shown in Figure 1 for the three specific options utilizing the BASF OASE® blue solvent technology (LB1, SIH and LB1-AFSC) as compared to the DOE/NETL Case 12 reference.

The Linde-BASF PCC technology options, integrated with a 550 MWe subcritical PC power plant, lead to increased net power plant efficiency from 28.4% reported in reference Case 12 to 30.9% (LB1), 31.4% (SIH), and 31.7% (LB1-AFSC) (Figure 1a). The increased efficiency and innovative, cost-effective design of the Linde-BASF PCC plant lead to significant reductions of total plant cost for the overall PCC plant integrated with 550 MWe coal-fired power plant (17.7% reduction for the LB1 option, 19.2% reduction for the SIH option, and 19.8% for LB1-AFSC) when compared with DOE/NETL Case 12 reference.

Table 13 summarizes the major annual operating and maintenance cost elements for the reference Case 12 utilizing MEA-based PCC technology, and for the three Linde-BASF PCC options.
The calculated COE for a 550 MWe PC power plant with CO_2 capture and compression is \$18.79/MWh to \$21.71/MWh lower than in DOE/NETL Case 12 reference (Figure 1c). Calculated COE values of \$128.46/MWh and \$126.49/MWh for LB1 and SIH options (including \$10/MT CO_2 TS&M costs), respectively, while utilizing SP-S methodology for TPC estimates, are equivalent to incremental COE increase for carbon capture and storage of 58.7% (LB1) and 56.2% (SIH), respectively, relative to the \$80.95/MWh estimated for a 550 MWe power plant without CO_2 capture.

Table 13. Summary of Annual Operating and Maintenance Expenses

Annual O&M Expenses for 550 MW PC Power Plant with PCC (2011$)				
	NETL 2011	Linde-BASF		
	Case 12	LB1-2011	SIH-2011	LB1-AFSC-2011
Total Fixed Operating Cost	64,137,607	57,356,056	56,777,693	56,557,758
Maintenance Material Cost	19,058,869	18,017,114	17,823,784	17,700,023
Water	3,803,686	3,595,777	3,557,193	3,532,493
Chemicals	24,913,611	23,551,836	23,299,117	23,137,338
SCR Catalyst	1,183,917	1,119,204	1,107,195	1,099,507
Ash Disposal	5,129,148	4,848,789	4,796,760	4,763,454
By-Products	0	0	0	0
Total Variable Operating Cost	54,089,231	51,132,721	50,584,050	50,232,815
Total Fuel Cost (Coal @ 68.60$/ton)	144,504,012	136,605,442	135,139,620	134,201,266

The cost of CO_2 (including \$10/MT CO_2 TS&M costs) decreases from \$66.49/MT CO_2 for the DOE/NETL Case 12 reference to \$51.81/MT CO_2 and \$50.48/MT CO_2 for Linde-BASF options LB1 and SIH, respectively (Figure 1b). Incorporating LB1-AFSC technology further reduces the cost of CO_2 to \$39.94//MT CO_2 without \$10/MT CO_2 TS&M costs

(Figure 1b), directly in line with the DOE target to reduce the cost of CO_2 derived from post-combustion capture technologies integrated with coal-fired power plants to less than \$40/MT CO_2.

D. Gap Analysis

This report has highlighted the major milestones and accomplishments of the Linde-BASF PCC technology to date, as well as the potential benefits of this technology when compared to other carbon capture solutions. However, along with these benefits there are a number of challenges that must be resolved before widespread adoption can be expected. Table 14 highlights key subsystems of proposed PCC technology along with the current and expected Technology Readiness Level (TRL) indicators.

Table 14. TRL Improvement of Key Subsystems of Proposed Linde-BASF PCC Technology

Subsystem	Current TRL	Comments	Expected TRL
Absorber and Stripper Columns	6	At larger column diameters, the importance of uniform liquid and gas distribution and proper design of feed inlets and gas/liquid offtakes become critical to achieve predicted performance of the target CO_2 capture rate and the minimum regeneration energy. In addition, a proper build and install strategy is required order to achieve the lowest cost option at scale.	7 (9)[1]
Heat exchangers and reboiler	6	Plate-fin exchangers have been used in the pilot plants and will be scaled up for the large pilot. The large pilot reboiler design will be selected as appropriate for the advanced stripper design configuration.	7
Stripper heat integration and recovery	6	Prior to the lean-rich heat exchange, the large pilot will incorporate a stripper inter-stage heater to use heat recovered from the CO_2-lean solvent to vaporize semi CO_2-lean solvent from an intermediate section of the stripper column. Detailed design has shown the energy reduction possible and this will be validated in the large pilot.	7[2]
Materials of construction	6	Several materials including carbon steel, different stainless steel options, fiberglass reinforced plastic (FRP) and concrete sections with polypropylene in-liners have been tested and evaluated in the pilot plants. The materials for the large pilot will be specified based on the results from the current pilot plant analysis.	7
Emission control	6	Solvent emissions minimization well below the air emissions compliance limits is a key success factor for commercial implementation of a solvent based post-combustion capture system. Assessment of the key operating parameters and a flue gas aerosol reduction options will be further validated at the proposed large pilot.	7
Solvent Management	6	Scale-up involves management of a much larger inventory of solvent which introduces complexity in the logistics of delivery and storage. Experience from other amine-based commercial systems, such as intermediate solvent storage and delivery and solvent reclamation and recycle, will be consideredfor the large pilot.	7

1, TRL 9 based on Linde related experience in building up to ~12 m diameter columns for other commercial applications
2,This has been validated in other commercial scale amime operations and will be applied in the large pilot.

Current TRL indicates the readiness level at the current stage of development, while expected TRL indicates readiness by the time learnings and results of the current large scale pilot testing period have been evaluated and effectively integrated into the process technology. The proposed Phase 2 project will address the identified technology gaps and pave the path forward for large scale commercialization of Linde-BASF OASE® blue technology. Below is a more involved discussion of two major areas of improvement that are required to address the cost and efficiency of any future commercialization.

Aerosol Formation, Solvent Emission and Prevention

Significant experimental and theoretical studies have been performed by RWE in Niederaussem and Linde-BASF at the Wilsonville, AL PCC pilot plant related to the mechanisms of aerosol formation in the flue gas stream and its consequences on solvent losses throughout the absorber column [4, 7]. It was established that one of the major unit operations influencing the number of fine, submicron size particles in the flue gas is a Wet Electrostatic Precipitator (WESP). As Figure 8 illustrates, increased voltage (above 15 kV) applied to the WESP leads to a significant reduction in the number of > 50 nanometer particles at a concentration of < 10^4 particles/cm^3, but simultaneously increases the concentration of very fine particles (< 50 nm) to a level of > 10^6 particles/cm^3. Simultaneous measurement of the amine concentration in the treated gas exiting the absorber (expressed as Total Hydrocarbon (THC) in Figure 5) and applied WESP voltage validates a close correlation between solvent losses and concentration of very fine particles (<50 nm) caused by utilization of WESP [Ref. 7].

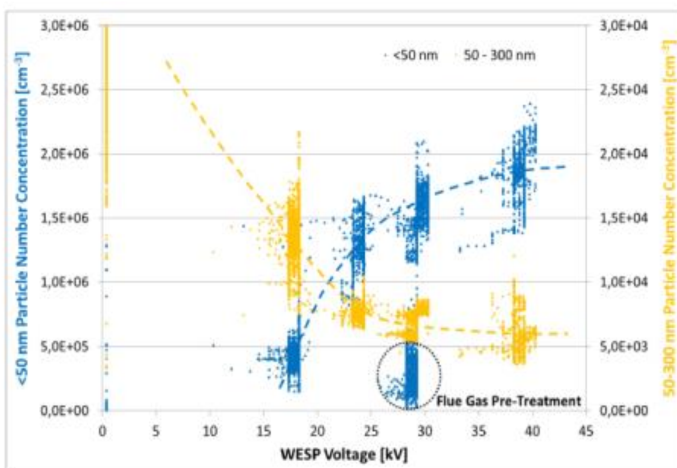

Figure 8. Influence of WESP voltage on fine particle size distribution and concentration. <50 nm particle number concentration are represented by blue dots, while 50-300 nm particle number concentration are represented by yellow dots.

As concluded by RWE studies, the solvent/amine losses from the absorber could be significantly reduced either by limiting the concentration of fine aerosol particles (<50 nm) to < 10^4 particles/cm^3 or by promoting aerosol growing for easy separation by conventional methods (water wash, demister etc.).

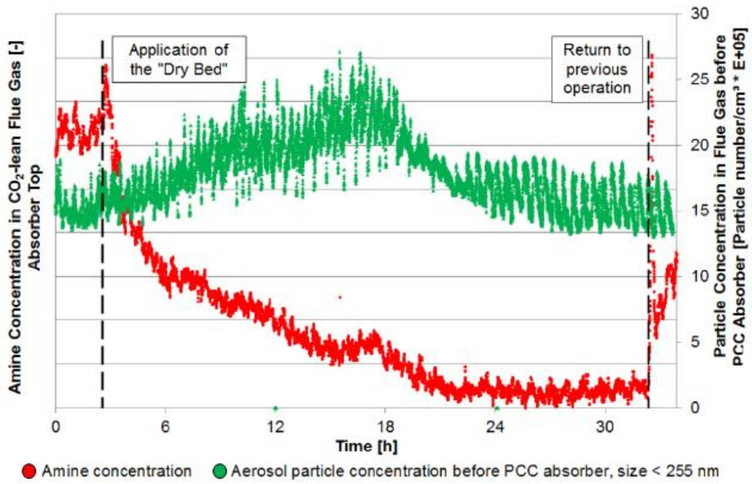

Figure 9. Effect of Linde-BASF patented dry bed emission control system on solvent emissions from the absorber column.

Linde and BASF have developed a patented "dry bed" wash absorber column configuration that reduces solvent emissions from the absorber. The absorption section of the pilot plant at Niederaussem consists out of four beds with the option to leave out the upper one. This operational configuration is named "Dry Bed". Figure 9 illustrates the effect of this Linde-BASF patented "dry bed" wash absorber column configuration on amine reduction. Although the wet electric precipitator produces a very high number of ultra-fine aerosol droplets in the flue gas before the absorber (shown in green), it is still possible to reduce the amine emissions out of the capture process significantly by activating the "dry bed" (shown in red).

Isokinetic tests were performed at Linde-BASF PCC Pilot Plant in Wilsonville in 2015 to establish the influence of PCC process parameters on amine losses. For flue gas containing a high aerosol particle concentration (> 10^5 particles/cm^3), it was found that the following process parameters reduce amine losses 5-10 times when combined (for flue gas containing a high aerosol particle concentration, as was experienced at the pilot plant in Wilsonville, AL):

- Higher CO_2-Lean Solution Return Temperature to Absorber
- Higher Absorption Intermediate Cooling Temperature
- Increased Absorber Pressure
- Reduced Treated Gas Temperature

In addition, a proprietary method for flue gas pre-treatment to reduce aerosol levels entering the absorber and the resultant amine losses reduction was tested at the Wilsonville PCC pilot plant in December 2015. The measurement results indicate that a nearly ~30% reduction in the concentration of fine particles in the flue gas can be achieved with this flue gas pre-treatment solution.

Considering the significance of "quality of flue gas" (expressed as number of fine particles per cm^3) on amine losses, in preparation for the final design of Linde-BASF large PCC pilot plant demonstration, comprehensive onsite aerosol measurements of the flue gas at the Abbott Power Plant were performed in February 2016 by the Aerosol and Air Quality Research Laboratory (AAQRL) of Washington University in St. Louis, led by Professor Pratim Biswas [Ref. 8]. The aerosol properties were measured at five operating conditions of the power plant: soot blow in boilers, FGD bypass, reheat burner off completely, reheat burner operated at 42% capacity, and reheat burner operated at 27% capacity (normal capacity conditions subject to opacity compliance requirements on the particular testing day).

The AAQRL staff installed the aerosol sampling and monitoring system close to Abbott Power Plant's online continuous emissions monitoring system (CEMS) sampling ports located between the reheat burner and the stack, close to the location where the flue gas would be withdrawn for the CO_2 capture. A scanning mobility particle sizer (SMPS with a differential mobility analyzer and a condensation particle counter, TSI

Inc.) and an aerodynamic particle sizer (APS, TSI Inc.) were used to measure the number concentrations and size distribution of fine particles under the five operating conditions mentioned above.

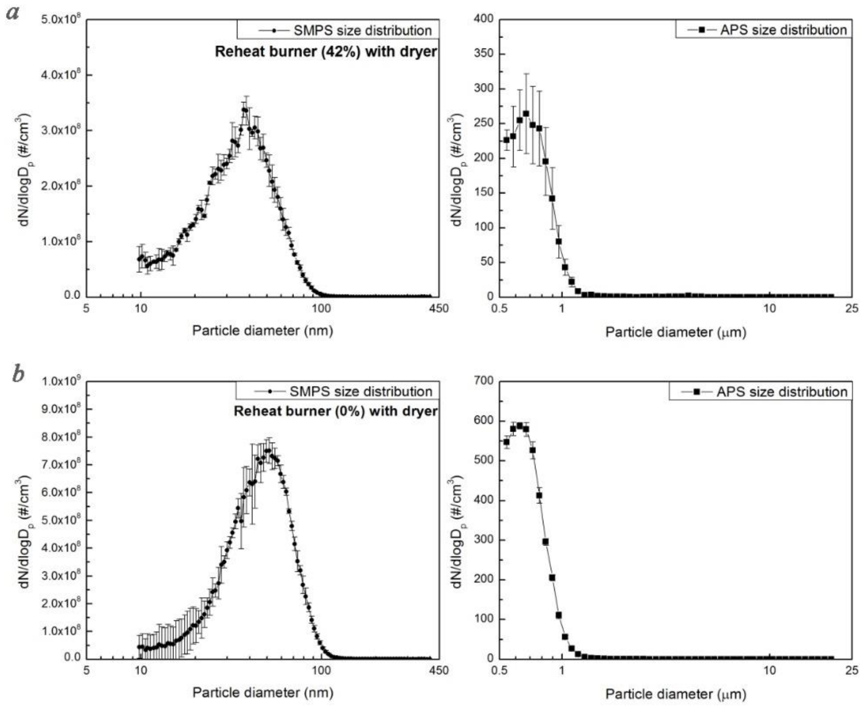

Figure 10. Particle size distribution measurements upstream of the Abbott Power Plant stack. Only two reheat burner conditions are shown (panels a and b), but the general data trend of high small nanoparticle concentration in the flue gas is depicted in the results of all process test conditions described in the report by the Air Quality Research Laboratory (AAQRL).

Figure 10, with qualitatively similar measurement results, clearly shows an extremely large concentration ($> 10^8$ particles/cm^3) of very fine particles (<100 nm, with the mean particle size at 40-50 nm) in all samples.

As a result, it was concluded that proper installation and testing of available flue gas pre-treatment options will be critically necessary before and during construction of the proposed large pilot PCC plant integrated with the Abbott Power Plant facility.

Water and Wastewater Management

The Phase 1 study has identified that the 15 MWe large pilot plant requires a cooling tower with a circulating water rate up to 8,600 GPM to provide the required cooling duty. Consequently, this will result in discharge of up to 37-46 GPM blowdown wastewater based on the number of concentration cycles adopted at Abbott power plant's exiting cooling towers. As a conventional option, the blowdown water is planned to be discharged to the local sanitary district.

The cooling tower blowdown needs to be permitted before it can be discharged to the local sanitary district. The large volumetric flow rate of blowdown water can result in permitting capacity issues as well as high permitting costs. To minimize the wastewater discharge and reduce the usage of fresh water as well, the additional options need also be assessed to identify the best option:

- Pre-filtration and Reverse Osmosis (RO) treatment of blowdown water. Commercial RO systems are widely available. With RO treatment, a large portion of the wastewater (e.g., 75%) can be recovered and then reused as makeup water for the cooling tower and only a small portion needs be discharged. Besides the reduced volume of discharge, the cost of installing and operating a RO system compared with permitting cost without any treatment is another factor to be considered.

- Softening treatment of cooling tower makeup water. Fresh water (e.g., city water) can be softened by removing scale forming salts (Ca, Mg, etc.). A minimal amount of chemical additives is required based on the quality of Champaign water. The use of softened feed water will allow much more concentration cycles in the cooling tower (e.g. 50 to 100 cycles and the cost-effective point depends on water quality and disposal costs). Compared with 3 to 4 concentration cycles practiced in the existing cooling towers, this can significantly reduce the volumes of blowdown discharge as well as fresh water makeup. A variety of softening technologies are commercially available with robust operational reliability (e.g., no membrane fouling) and low power requirements.

- Use of blowdown water from Abbott's existing cooling towers with modified design of large pilot plant cooling tower. Large quantities of blowdown water from Abbott's existing cooling towers are available. These water streams are relatively clean because only few cycles (e.g., 3 to 4 cycles) are used compared with common practice (e.g., 8 to 10 cycles). To accommodate the use of Abbott blowdown as water makeup, the modification and tuning of the large pilot cooling tower design is necessary.

In addition, the large pilot plant also generates a significant amount of flue gas condensate (estimated at 35 GPM) from the DCC. This wastewater stream contains typical flue gas contaminants, carbonates, sulfites and sulfates, which is similar by nature to the scrubbing water in the flue gas desulfurization (FGD) unit but has much lower concentrations of the contaminants. Therefore, this could be used as a potential source of process water for Abbott's FGD scrubber. Reuse/recycle of the DCC process condensate in the cooling cycle as make up water is also actively being explored as a wastewater management strategy. For the same reason, the reuse of flue gas condensate as FGD process water or cooling tower makeup water could both eliminate the wastewater discharge and reduce the FGD water usage.

E. Pilot Plant Design requirements and Description

The Abbott Power Plant was selected as the host site for the proposed capture plant installation and testing. Abbott's maximum steam production capacity is about 800,000 lb/hr (363,200 kg/hr). Of the total seven boilers, three are coal based, all of which are of the chain-grate stoker design. The remaining four are fired by natural gas. The downstream system of the coal-fired boilers is completely separate from that of the natural gas fired boilers, thereby assuring testing can meet project goals and requirements.

Amongst the three coal boilers, two (#5 and #6) are each capable of producing up to 150,000 lb/hr (68,100 kg/hr) of steam and another one (#7) has a capacity of producing 176,000 lb/hr (79,904 kg/hr) of steam. An Illinois high sulfur coal is burned and the coal is delivered to the plant via semi-trucks. Electrostatic precipitators and a wet FGD scrubber are used in conjunction with the coal boilers to remove particulate and SO_2 from the flue gas. A reheat gas burner downstream of the wet FGD scrubber reheats the flue gas to the required temperature (~200 ^oF) to insure opacity compliance, before it passes to the CEMS and to the plant stack. The three coal boilers combined are permitted to produce up to 350,000 lb/hr (158,900 kg/hr) of steam, which is limited by the capacity of the FGD scrubber to process 425,600 lb/hr (193,049 kg/hr) flue gas (35 MWe).

The standard operating procedure of Abbott Power Plant is to run a maximum of two boilers simultaneously or a single boiler. When the coal-fired boilers are operational to produce 135,000 lb/hr of steam (61,290

Table 15. Large Pilot Plant Basis for 15 MWe

		Flue Gas Specification		Treated Gas	Total Captured CO_2
Description	**Unit**	Case 1 (Straight FG Flow)	Case 2/3 (FG with CO_2 recycle)	Case 2/3 (FG with CO_2 recycle)	Case 3 (CO_2 recycle at higher pressure)
Operating pressure	bar (psi)	1.0 (14.9)	1.0 (14.9)	1.0 (14.9)	3.4 (49.3)
Operating temperature	°F (°C)	200 (93.3)	200 (93.3)	104 (40)	104 (40)
Total Volumetric Flow	(Nm^3/h)	78,353	65,621	63,424	1,833
Total Mass Flow	lb/hr (kg/hr)	163,321 (74,081)	163,903 (74,345)	142,967 (64,849)	22,841 (10,361)
Composition:					
CO_2	mol%	5.7	10.4	1.1	97.7
N_2	mol%	68.8	72.7	78.7	0.0
Ar	mol%	0.8	0.9	0.9	0.0
O_2	mol%	10.3	10.9	11.8	0.0
H_2O	mol%	14.4	5.2	7.5	2.2
SO_2	ppmv	68.0 (max 200)	64.0	N/A	N/A
SO_3	ppmv	tbd	tbd	N/A	N/A
NO_x	ppmv	tbd	200	N/A	N/A
Chlorides	ppmv	tbd	tbd	N/A	N/A
Dust	lb/SCF (mg/Nm^3)	tbd	tbd	N/A	N/A

kg/hr), equivalent to a nominal 15 MWe output, the volume of flue gas produced is estimated at 171,009 lb/hr (77,638 kg/hr). The flue gas will be directed to the PCC plant after the FGD, reheater and post Continuous Emissions Monitoring System (CEMS) which maintains the layout that the power plant has been permitted for. This approach will reduce the risk of re-permitting that could negatively impact the project's budget and/or schedule. The anticipated flue gas feed for the capture system would be the exit stream of the FGD after the flue gas reheater.

The flue gas specification in Table 15 indicates that the CO_2 concentration of the Abbott plant flue gas is low compared to conventional pulverized coal-fired power plants (presumably since the Abbott Power Plant has Stoker coal-fired boilers with a high excess air flow). While the as-received flue gas will be directly treated in the base scenario, other tests will also be conducted with the recycle stream of the captured CO_2 fed to the absorber inlet to increase the CO_2 concentration of the flue gas influent. Such tests will represent the flue gas conditions typical of conventional pulverized coal-fired power plants to operate the CO_2 capture pilot at a nominal CO_2 capture capacity of 300 ton/day (272 metric tonne/day).

Three test cases are planned in the proposed Phase 2 project:

Case 1: Treat as-received flue gas: Treating the as-received raw flue gas (171,009 lb/hr (77,638 kg/hr) containing the low concentration CO_2 (5.7%mol)

Case 2: Treat flue gas with CO_2 recycle: Recycling a portion of the captured CO_2 to the absorber inlet to increase the CO_2 concentration from 5.7%mol (without recycle) to 10.3%mol (with recycle). The flow rate of the raw flue gas withdrawn is slightly lower than Case 1 due to the CO_2 recycle.

Case 3: Treat flue gas with CO_2 recycle and stripping operation at a higher pressure: Flue gas conditions are similar to Case 2 but the stripping operates at 3.5 bar compared with 2 bar stripping in Case 2.

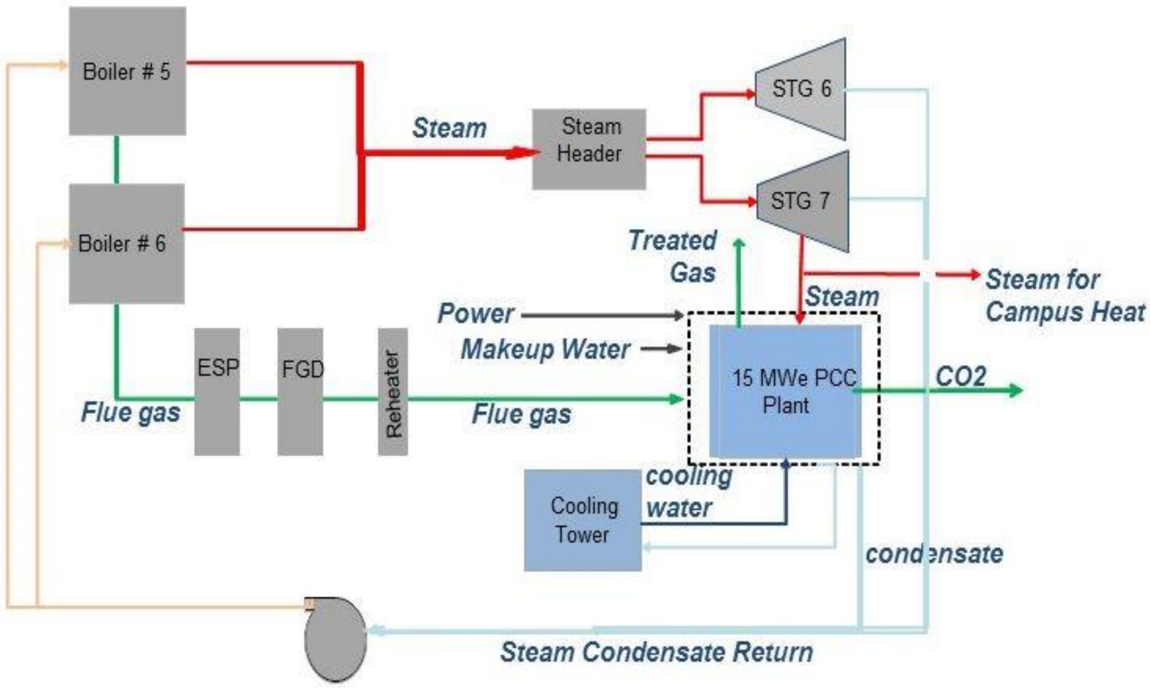

Figure 11. PCC Pilot Plant Integration with Power Plant with Utilities

The proposed host site is managed by the UI, and the host site is prepared to provide site access and utilities in support of the proposed project. A simplified PFD of Linde's pilot plant, along with tie-in points with Abbott Power Plant is shown in Figure 2. Figure 11 demonstrates interface streams from the

Table 16. Utilities supplied by Abbott Power Plant for the 15 MWe pilot plant

Utility	Flow	Conditions
LP Steam	up to 17,040 kg/h	50-70 psig (3.4-4.8 bar, gauge)
Cooling Water Makeup (City Water)	up to 132 GPM (30,000 kg/h)	85° F (30° C)
Electrical Power	up to 462 kW	110/220/480 volt, single/three phases

power plant perspective. The major utilities provided by Abbott Power Plant for the pilot plant are listed in Table 16.

Figure 12 shows a potential site for the proposed new pilot plant, located NW of the power plant in an open lot. The proposed space provides sufficient room for the construction of the capture system and an auxiliary cooling tower needed to supplement the needs of the capture system. Linde and BASF will be responsible for loading new and disposing of used solvent, while the Phase 2 project will manage the discharge of the waste water from the direct contact cooler and blowdown water from the cooling tower of the PCC pilot plant with appropriate environmental permitting.

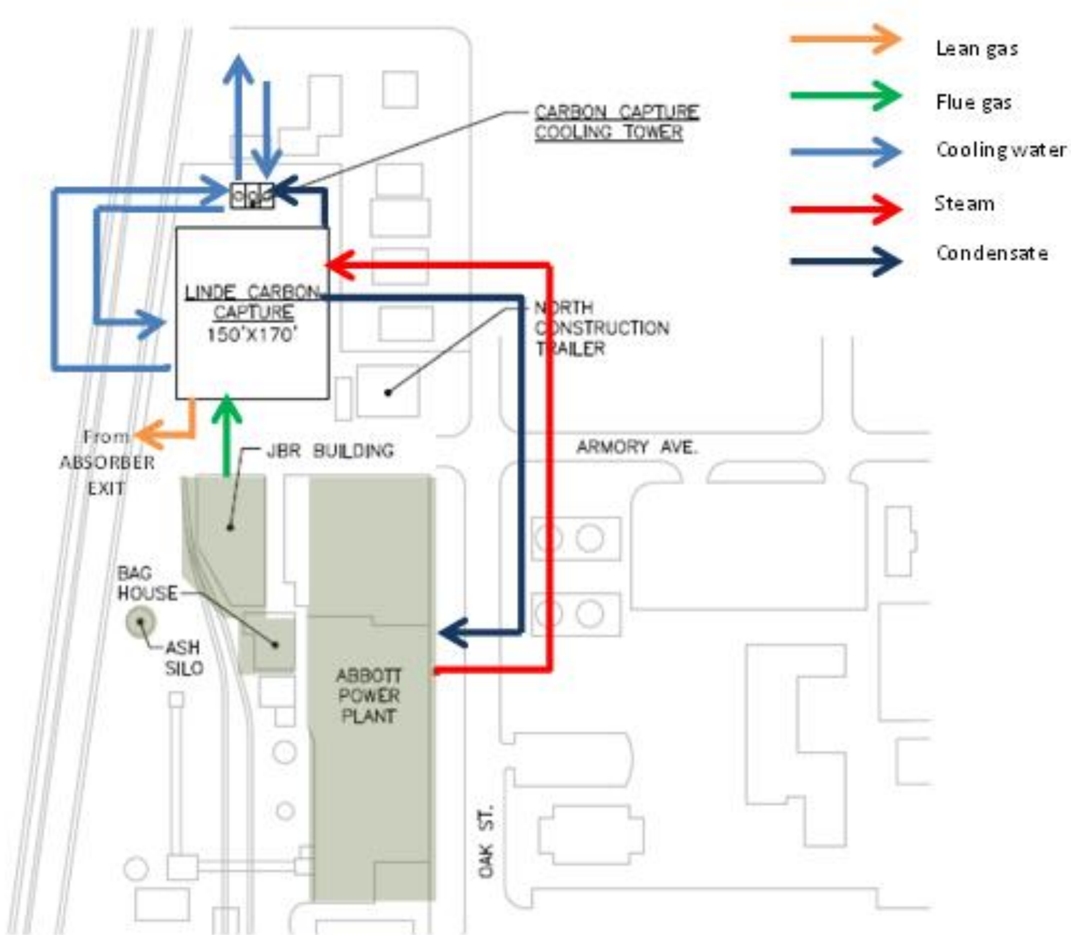

Figure 12. Potential site layout plan for the PCC unit

F. Lessons Learned

Technical

- Significance of solvent regeneration at high pressure (up to 3.5 Bar) on capital and operating cost reductions for a PCC plant integrated with CO_2 compression and drying.
- Significance of flexible reboiler design to allow proper PCC process dynamics during rapid power plant load fluctuations. These dynamics are achieved with an advanced reboiler design including a variable heat transfer area for optimum balance between heat transfer rate and potential thermal degradation of solvent.
- Optimization of PCC process configuration to maximize waste heat utilization and ultimately minimize solvent regeneration energy consumption. A new Stripper Inter-stage Heater (SIH) is included in the current design of the proposed PCC plant at Abbott Power Plant UIUC. This inter-stage heater utilizes part of the high temperature thermal energy from the CO_2-lean solvent exiting the desorber/stripper to heat and vaporize semi CO_2-lean solvent taken from an intermediate section of the stripper and return the heated solvent back to the stripper, recovering significant heat losses in the desorber/stripper column. Additional methods to reduce energy consumption will be evaluated. This includes a paper study on the utilization of external waste heat, as well as one on the advanced flash stripper configuration [Ref. 9 and Ref. 10] to understand trade-off between incremental energy reduction and additional possible capital cost penalties.
- Significance of aerosol formation on solvent losses and related emission issues. Significant work completed and results compiled in Niederaussem, additional tests at NCCC, and initial tests of the flue gas quality at Abbott Power Plant have prompted important consideration of options for aerosol control treatment for the flue gas prior to its entry into the absorber column of the proposed pilot. Further testing will be conducted at Abbott Power Plant to determine the effects of these innovative flue gas aerosol control treatment options on minimizing solvent losses from the PCC plant.
- Presentations which focus on the opportunity to create a center for utilizing captured carbon have spurred interest from other technology developers in CO_2 utilization. They have welcomed the opportunity to conduct large pilots that would technically de-risk these utilization technologies.

Stakeholder Engagement

- From the end user (power plant) perspective, implementation of this project has initiated the development of an approach that can be shared with other power plants. These end users would consider retrofitting of their plants for carbon capture.
- A variety of stakeholder groups and associations have appreciated the opportunity to be educating in the value and regional economic impact that CCUS can have on the economy. They consider this large scale pilot an opportunity to evaluate and demonstrate these impacts.
- Utilities have welcomed the concept of the proposed host site, Abbott Power Plant at the University of Illinois, to become a training ground for the operation and maintenance of capture facilities.

Permitting / Regulatory

- The Phase 1 enabled the team to appreciate the importance of water demand on the permitting process. It became very clear that the largest permitting cost surrounding water management. This incentivized the team to develop methods to reuse / reduce water usage, thereby reducing permitting costs.

Workforce Development / Training / Education

- Information sharing with the Association of Illinois Electric Cooperatives (AIEC) has uncovered a set of stakeholders that are strong advocates for CCUS. Networking through AIEC has resulted in developing workforce development opportunities for veterans.
- The project has created discussion amongst faculty group at both University of Illinois and Southern Illinois University to incorporate course work relevant to CCUS. Plans are also developing to have undergraduate students from energy studies disciplines participate in the testing and evaluation of the capture system.
- This project has incentivized interactions with community colleges to train future operators of the capture facilities. The involvement of Illinois Eastern Community Colleges has been instrumental in providing a pathway to employment for out-of-work mine workers.

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7. S. Rigby; Results from the Testing on a 1MWel Advanced Aqueous Amine-Based PCC pilot Plant in Wilsonville. PCCC3 and SaskPower Symposium. Regina, Saskatchewan, September 2015

8. Z. Li, Y. Wang, P. Biswas: Aerosol Measurements in Coal Combustor Exhaust Gas at the Abbott Power Plan, IL, February 2016

9. Gary Rochelle; Tarun Madan; Yu-Jeng Lin; Apparatus for and method of removing acidic gas from a gaseous stream and regenerating an absorbent solution. United States Patent Application. Pub. No.: US 2015/0246298 A1, September 3, 2015.

10. Gary Rochelle; Tarun Madan; Yu-Jeng Lin; Regeneration with Rich Bypass of Aqueous Piperazine and Monoethanolamine for CO_2 Capture. I&EC Research, February 18, 2014.

APPENDIX: PRODUCTS

Publications, Conference Papers, Presentations

1. "Progress on the developments of an advanced aqueous amine-based post combustion CO_2 capture utilizing BASF's OASE® blue technology" 2015 Carbon Management Technology Conference Sugarland, Texas; November 18, 2015

2. "Center for Utilization of Captured CO_2 (CUC- CO_2): Creating a Market for Captured CO_2", ACI's 6th Carbon Dioxide Utilization Summit, New Jersey, USA February 24-25, 2016.

3. "Phase 1 Results: Large Pilot Scale Testing of Linde/BASF Post-Combustion CO2 Capture Technology at the Abbott Coal-Fired Power Plant", 2016 NETL CO_2 Capture Technology Project Review Meeting, August 08 - 12, 2016, Pittsburgh, PA.

4. "Creating Markets for Captured Carbon: Retrofit of Abbott Power Plant and Future Utilization of Captured CO_2", November 2016, GHGT-13, Lausanne, Switzerland.

5. "Retrofitting Plants for Carbon Capture and Utilization: Redefining The Carbon Supply Chain", The 2017 Carbon Capture Utilization & Storage Conference, Chicago, IL, April 10-13, 2017.

Journal Articles

1. "Creating markets for captured carbon: Retrofit of Abbott Power Plant and Future Utilization of Captured CO_2", Kevin C OBrien, Yongqi Lu , Vinod Patel, Sallie Greenberg, Randall Locke, Michael Larson, Krish R. Krishnamurthy, Makini Byron, Joseph Naumovitz, David S. Guth, Stephen J. Bennett, 13th International Conference on Greenhouse Gas Control Technologies, GHGT-13, 14-18 November 2016, Lausanne, Switzerland.

Websites or Other Internet sites

Web-based information sharing for the team members was constructed using the University of Illinois' BOX application. This provided for secure sharing of project related information.

Technologies or Techniques

None

Inventions, Patent Applications, and/or Licenses

None

Other Products

None